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PROPOSED AURAL NONDETECTABILITY LIMITS FOR ARMY MATERIEL

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March 1985
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U. S. ARMY HUMAN ENGINEERING LABORATORY
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The parameters which affect the propagation and detectability of sound are discussed and assessed for the purpose of revising the aural nondetectability limits of MIL-STD-1474 (1979). The factors considered are geometric spreading, atmospheric absorption, ground effect, atmospheric turbulence, refraction due to wind and temperature gradients, barriers, foliage, threshold of hearing, psychoacoustic factors, and background noise at the listener's location. Examples are given of the effect on sound propagation of varying the parameters, and several suggestions are offered for field expedient measures to control or detect sound.

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Standard conditions for sound propagation and detectability are proposed, along with two assumed background noise levels. These conditions and background noise levels form the basis for two proposed nondetectability limits. These limits, expressed in 1/3-octave bands, are provided for critical and typical military scenarios and a rationale for selecting between them is developed. Measurement procedures for determining conformance with the limits and an explanation of the methods and rationale used in computing the limits are also presented.

The proposed limits are intended to provide nondetectability under most conditions likely to be encountered. However, sound propagation conditions are identified which might allow materiel meeting the limits to be detected.

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PROPOSED AURAL NONDETECTABILITY LIMITS FOR ARMY MATERIEL

INTRODUCTION

The current design limits for aural nondetectability of Army materiel are contained in Section 5.2 of MIL-STD-1474B, "Noise Limits for Army Materiel," which was published in 1972. These limits provide recommended sound pressure levels (SPL) not to be exceeded for Army materiel having a tactical requirement for aural nondetectability. These limits were based upon the best data available at the time and were deliberately chosen to be conservative. They provide "actual detection distance for specific conditions of terrain, wind, background noise, etc., and may occasionally be greater, but more often will be shorter" than the nondetectability distance specified in the standard.

These limits were based upon the following assumptions:

a. A very quiet background noise level at the listener's location.
b. The hearing acuity of a normal young adult.
c. Geometric spreading of sound through the atmosphere.
d. Molecular absorption.
e. A steady broadband noise source which does not include pure tones.

During the past 10 years, a significant amount of research has been conducted on the problem of outdoor sound propagation and signal detection. There is much new information on sound attenuation caused by ground effect; human ability to distinguish sounds from a background noise; variation of background noise with location; and prediction of molecular absorption.

The conservatism of the present limits assures nondetectability under most noise conditions. However, these very stringent limits may also have adverse effects on the development of quieter materiel. Also, many situations exist where it is not necessary for materiel to be inaudible under worst case conditions. Many current military scenarios do not involve aural nondetectability in extremely quiet environments; thus, materiel developed for less than worst case scenarios can be designed at lower cost, lower weight, and reduced size. Moreover, in tactical areas having more typical background noise levels, a modest degree of noise reduction may make materiel nondetectable. Accordingly, two limits tailored to specific classes of situations are proposed.

The limits to be specified must be both realistic and accurate. Realism requires that an item be nondetectable under a reasonable percentage of possible operating conditions. Accuracy requires that the nondetectability limits be based on the most current and credible technical information.

PURPOSE AND OVERVIEW

The foregoing considerations have prompted a reexamination of the non-detectability limits of MIL-STD-1474 and the writing of this report. The purposes of this report are to (a) review the current state of knowledge of sound propagation and detectability and, (b) propose new aural nondetectability limits and a scheme for choosing a particular limit based on a realistic assessment of military scenarios and the latest technical information on sound propagation and detection.

PARAMETERS AFFECTING AURAL DETECTION OF SOUND

Each of the factors which affects the propagation and detectability of sound will be reviewed. They will be discussed in terms of their appropriateness for use in a military standard, and a standard, value, or condition will be recommended for each factor.

Background Noise Levels

General

The background noise level at the listener's location is probably the single most important factor for determining aural nondetectability. Figures 1 through 3 show background noise levels measured in a variety of reasonably quiet locations, both in the United States and other parts of the world. None of the levels shown are in industrial areas or near transportation or construction noise.

Variability of Background Noise Levels

Background noise is a major factor in establishing nondetectability. Examination of various background noise levels indicates that they can vary widely. Depending on the frequency region, the levels at the North Rim of the Grand Canyon and the surf at Wallops Island can differ by as much as 47 decibels (dB).

Background noise also varies significantly from moment to moment at a given location. Near communities, background noise can vary over a range of more than 30 dB (EPA, 1971); this variation is caused by aircraft, vehicles, industry, etc. As one moves further into the wilderness and away from manmade noise, this variation is typically reduced in magnitude. The lower level of these variations is called the "residual level," which is that constant level one measures when no single source can be identified.

In addition to moment-by-moment variations in level, the residual noise level at a given location varies with time of day: near communities the noise level decreases at night by about 10 dB. Again, as one moves further from communities, manmade noise decreases, and this diurnal variation is reduced.

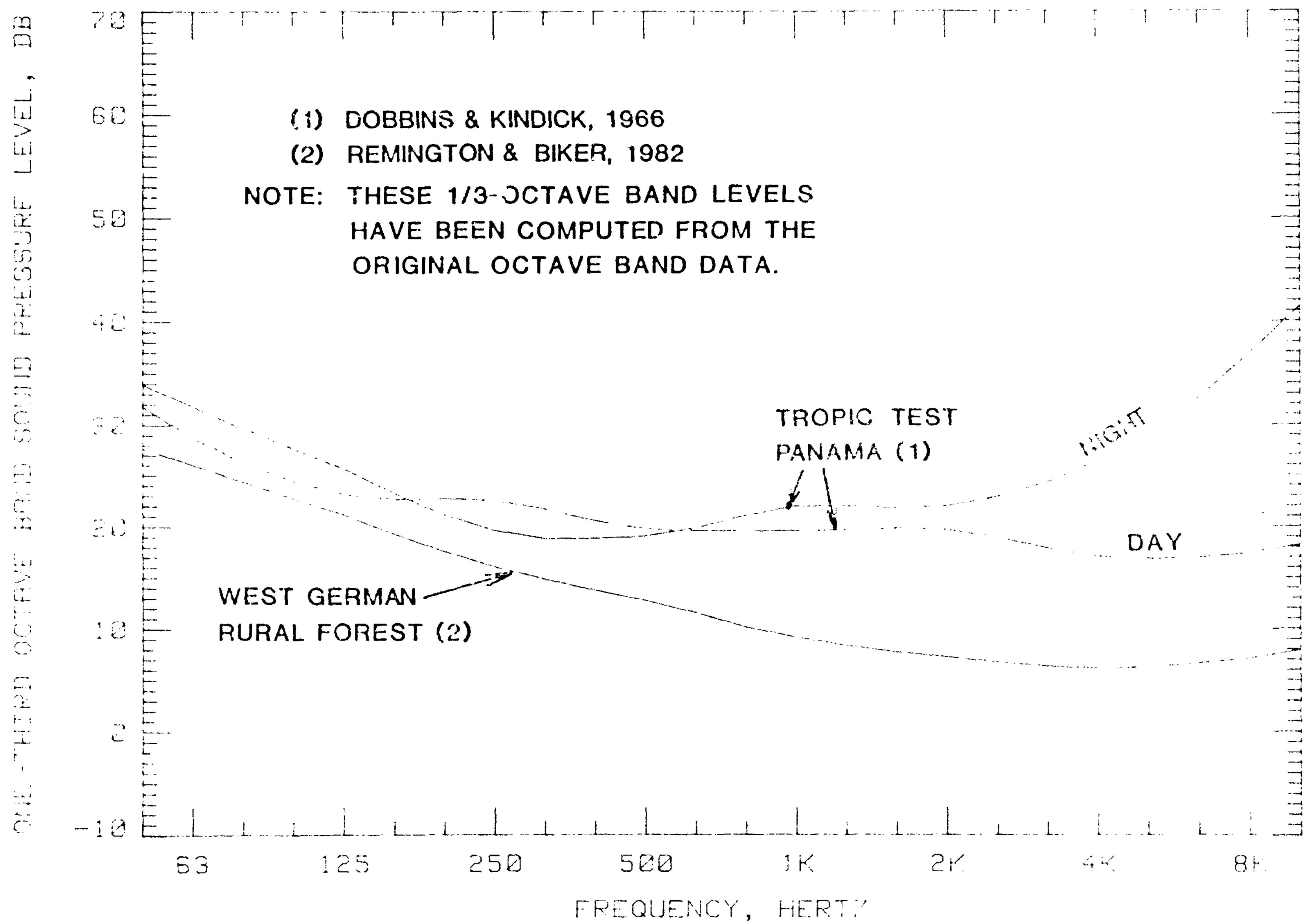


Figure 1. Mean sound pressure levels in a West German forest (daytime) and at the Tropic Test Center.

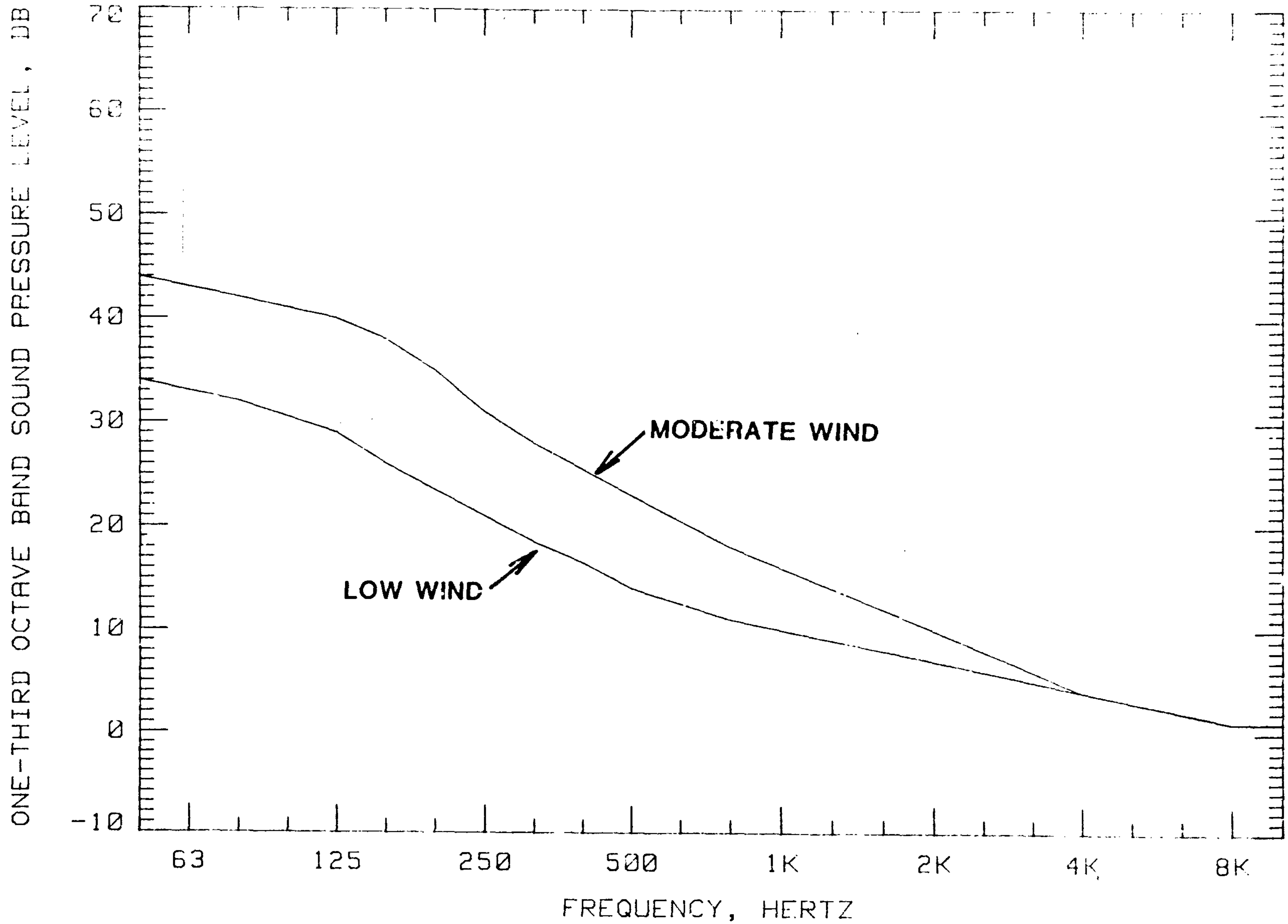


Figure 2. Mean daytime sound pressure level in the California desert (Fidell & Bishop, 1974).

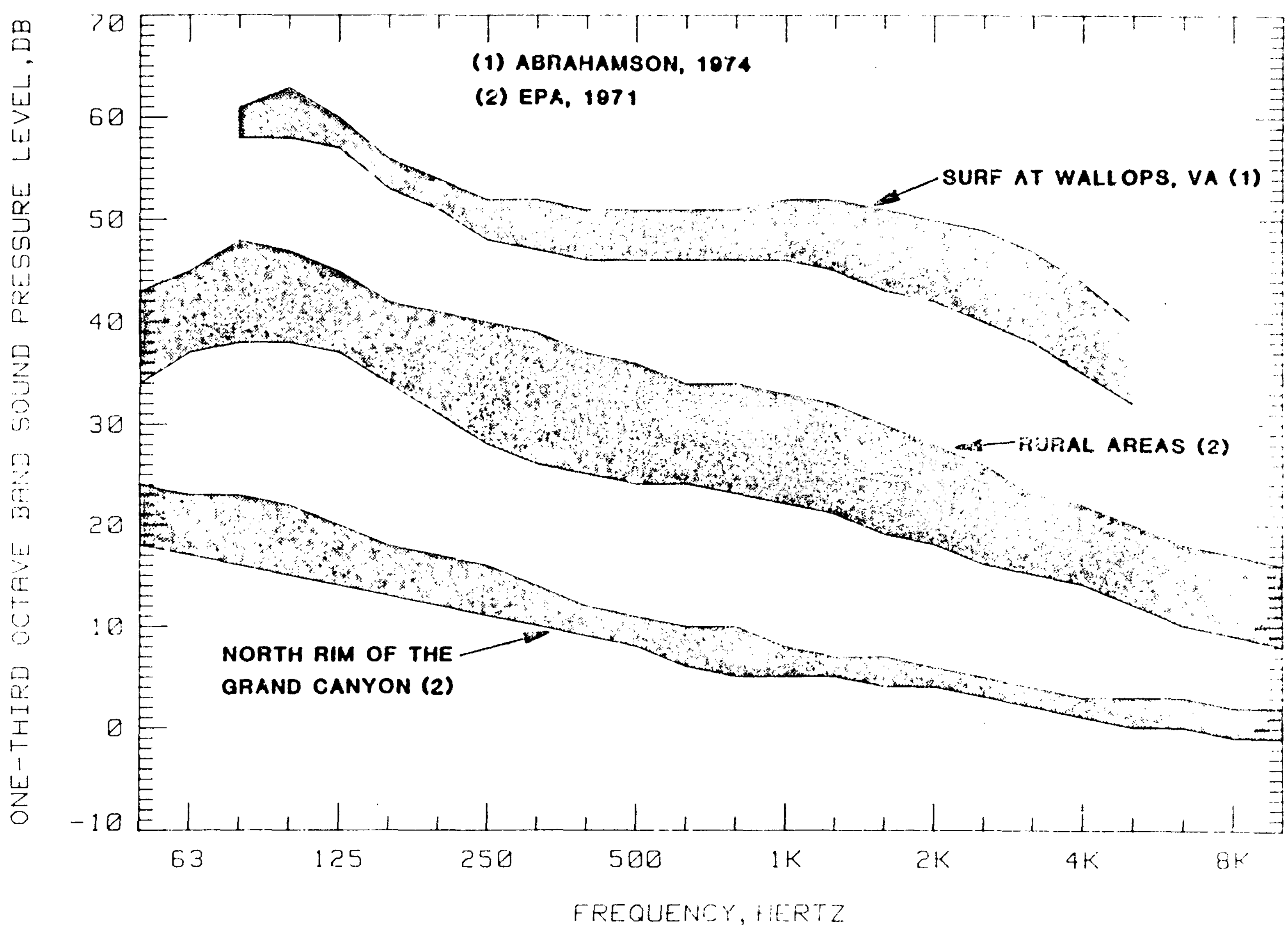


Figure 3. Range of sound pressure levels at several locations in the United States.

Sources of Background Noise Levels

Shaw and Olson (1972) and Piercy and Embleton (1979) have shown that the sound level at various locations around the world is dependent mainly upon their distance from cities, densely traveled roads, and industrial and construction sites. These background noise spectra peak at low frequencies and fall off at higher frequencies at the rate of 3-5 dB per octave. As can be seen from Figure 1, the major variation from this slope would be that produced by the presence of insects, as in a jungle. Insect noise tends to fill in the high frequency region to produce a flat spectrum or even a rising spectrum characteristic of nighttime jungles (Dobbins & Kindick, 1966).

The Environmental Protection Agency (EPA) has sampled the range of noise levels in many locations in the United States from the wilderness to the center of a city. The quietest daytime location they report is the North Rim of the Grand Canyon, with its residual noise level shown as the lower level of the shaded area in Figure 3. On the other hand, rural farm areas have a higher residual noise level (Figure 3). The difference between the very low noise level at the Grand Canyon and the level measured in rural farm areas is "representative of the contribution of man and machine" from two different distances (EPA, 1971).

Selection of Residual Background Noise Levels

For the purpose of proposing a revision to MIL-STD-1474, two residual sound pressure levels have been selected: one is representative of the quietest daytime level to be found at a significant distance from manmade noise; the other is the level typically found in rural areas closer to manmade noise. These background noise spectra will be used as the basis for calculating two aural nondetectability limits. The lower level will provide the basis for nondetectability limits applicable under the quietest of conditions around the world. The higher level will provide the basis for nondetectability limits for use under more typical conditions, similar to many situations the Army faces in the field.

The 1/3-octave band sound pressure levels, expressed in dB, for these two areas are shown in Table 1.

Distance to Highways and Communities

In accordance with these selections, it becomes necessary to calculate the distance to the closest heavily traveled road and the closest city of significant size which might result in these two residual sound levels. Piercy and Embleton (1979) have provided an approximation technique for determining the level at various distances from heavily traveled highways. Shaw and Olson (1972) have shown that typically the greatest source of community noise is that produced by traffic. In computing the distance required to reduce traffic noise to our two baseline levels, we have assumed 1000 vehicles (10 percent truck factor) per hour traveling at 50 mph. These are the computed distances: Grand Canyon, 16 km; rural, 4 km. Therefore, the two selected levels are typical of average noise situations at these specified distances from such sources of manmade noise like highways and communities.

TABLE 1

1/3-Octave Band Sound Pressure Levels (dB) for Quiet and Typical Areas

Frequency (Hz)	Area: Quiet (Grand Canyon)	Area: Typical (Rural Farm)
50	18	34
63	17	37
80	16	38
100	15	38
125	14	37
160	13	34
200	12	31
250	11	28
315	10	26
400	9	25
500	8	24
630	6	24
800	5	23
1000	5	22
1250	5	21
1600	4	19
2000	4	18
2500	3	16
3150	2	15
4000	1	14
5000	0	12
6300	0	10
8000	-1	9
10000	-1	8

Psychoacoustic Factors in Auditory Perception

A number of psychoacoustic factors can be identified that play a part in the ability of people to detect sounds or to discriminate among sounds. From the standpoint of aural detectability of equipment sounds, the more salient factors seem to be hearing sensitivity, temporal integration, listening conditions, nature of target sounds, and listener's efficiency.

Hearing Sensitivity

Absolute threshold, commonly referred to as the threshold of hearing, is the lowest sound pressure level of a tone or band of noise that can be detected 50 percent of the time. Thresholds are expressed in dB SPL or in dB HTL (hearing threshold level) referenced to audiometric zero (modal values for normal population). The threshold of hearing data used in the proposed detectability model described in this report is published in ISO R-226 (1961).

The threshold reflected in ISO R-226 represents the hearing sensitivity of young, normal, nonnoise-exposed persons. The hearing threshold of most military personnel is less acute. Noise-induced hearing loss develops first in the higher frequencies of hearing and progresses downward in frequency as exposure time increases. Walden, Prosek, and Worthington (1975) studied the hearing acuity of US Army personnel in three combat arms (infantry, artillery, and armor) having various amounts of military service. They found that even persons just entering the service had hearing acuity which was less acute than that reported in ISO R-226, particularly at frequencies of 4000 Hz and above. Surveys conducted among personnel of several other armies show essentially the same thing.

The most critical frequency region for aural detection of outdoor sounds is usually 250-500 Hz. This region contains most of the acoustical energy for many military noise sources and noise-induced hearing losses usually develop last and progress slowly in this portion of the hearing range. Thus, although we are assuming normal hearing sensitivity at all frequencies, little or no bias will be introduced into the detection model. Even though the average hearing level may be atypical in a military population, there are, nevertheless, many persons who retain normal sensitivity. It is only necessary for one person to detect sound produced by materiel.

Temporal Integration

Temporal integration refers to the fact that the auditory system integrates acoustic energy for a period of up to 200 ms (Garner & Miller, 1947; Zwislocki, 1960; Price & Hodge, 1976). If a 20-ms sound were just detectable, then 200 ms of the same sound would be detectable at a 10-dB lower intensity. The time constant of the human auditory system is about 200 ms. Thus, steady sounds, such as those produced by generators, would be detected at lower SPL's than impulsive and nonrepetitive sound sources, like weapons.

This fact has implications for the way equipment sounds are measured. Sound level meters typically have two settings for meter damping: "fast" and "slow." On the fast setting, the meter time constant is 125 ms; on the slow setting, the time constant is 1 second (ANSI, 1983). Our proposed detection model takes temporal integration into account by requiring that equipment noises be measured with fast meter damping and that the maximum meter deflection is the value to be recorded.

Listening Conditions

Moraural Versus Binaural Listening

Theoretically, the threshold for a sound heard with a person's two ears should be about 3 dB lower than for the same sound heard with only one ear. However, this relationship holds true only for pure tones and only when the listener's two ears are of exactly equal sensitivity (a rare occurrence) (Licklider, 1951). So for practical purposes, no special allowance should be made for binaural listening because the binaural/monaural difference is unpredictable and insignificant.

Quiet Versus Nonquiet

Absolute quiet does not exist; all practical listening conditions contain some background sounds. The masking effect of background sounds generally follows the "critical band" concept, wherein masking is maximal when the noise and signal are within the same critical band (Scharf, 1970). For practical purposes in predicting masking effects, critical bands may be approximated by 1/3-octave bands. Detection of a sound depends on the signal-to-noise (S/N) ratio within each critical band (S is the materiel-produced noise; N is the background noise). The specific values for the S/N ratio and the rationale are included in the next section. Recent research on low-frequency masking has resulted in a slight modification of the weighting factor for 1/3-octave bands of masking noise below 250 Hz (Fidell, Horonjeff, Teffeteller, & Green, 1980). These weighting factors are included in the proposed nondetectability limits and produce an increase of no more than 2 dB in the limit.

Nature of Sounds to Be Detected

The aural nondetectability limits of the current MIL-STD-1474 assume that materiel sounds are broadband in spectrum and relatively steady in level: we have used these assumptions in the proposed model as the "typical" situation. This implies that detection will occur when the S/N ratio in a particular 1/3-octave band is greater than zero (and, of course, the materiel sound level exceeds the threshold of hearing). In some noteworthy cases, intermittent sounds can be detected at negative S/N ratios. According to Miller, Heise, and Lichten, (1951), speech sounds can be understood at S/N ratios as low as -12 dB. And Ollerhead's (1971) report indicates that helicopter blade slap was detectable at a level 5 dB below the ambient background noise.

Another aspect of materiel sounds that may affect their detectability is the presence of pure tones or very narrow bands of noise. Pure tones give materiel a distinctive sound (turbine whine, for example) which not only makes them more detectable but also makes them more distinguishable as a particular kind of target.

It is realistic to assume that the number of materiel sounds containing pure tones or having an intermittent time history is relatively small. For simplicity's sake, no correction is included for either of these characteristics.

Listener Efficiency

The classical concept of a threshold of hearing as discussed in this report has been found to be deficient, especially in describing the detectability of signals in noise, in that it does not take into account the listener's response bias. This can be demonstrated by merely instructing listeners to exercise varying degrees of certainty in making their responses: the result will be a set of differing response curves. The Theory of Signal Detectability (TSD) presents a method for separating the effects of observers' criteria from the detectability of sounds and determining the relative value of each of the two aspects of the sound detection process (Tanner & Birdsall, 1958; Deatherage, 1972; Fidell & Bishop, 1974). By taking into account the false alarm rate and the decision risk factors that influence false alarms, TSD provides a more powerful concept of detectability than the classical concept of a threshold by defining a statistic, d', which reflects the sensory contribution to human signal detection. TSD has been incorporated into some models of equipment sound or noise detectability (Fidell & Bishop, 1974; Fidell, Horonjeff, Teffeteller, & Green 1980; Fidell & Horonjeff, 1982), including the model used to calculate the nondetectability limits proposed here.

The following TSD parameters are assumed by the proposed model: the listener's hit probability is 0.5, false alarm rate is 1 percent, and the listener is 40 percent as efficient as an ideal observer. The assumed value of d' is 2.32, which is defined by the assumed hit probability and false alarm rate. These parameters are the same as those that would be involved in the measurement of audiometric thresholds and are characteristic of highly motivated listeners attending to auditory signals in a laboratory experiment.

PARAMETERS AFFECTING SOUND PROPAGATION

General

The propagation of sound through the atmosphere, from a source to a listener, is controlled by a number of wave propagation phenomena, each producing different rates of attenuation versus distance for each frequency. Although there is interaction between some of these phenomena, we tried to address them individually so that each one may be considered separately or disregarded if appropriate.

Geometric Spreading

Sound pressure decreases inversely with distance at all frequencies. For a point source (one which radiates sound uniformly in all directions), sound decreases at a rate of 6 dB per doubling of distance or 20 dB per tenfold increase in distance. Measurements will exhibit this behavior providing there are no reflecting surfaces nearby like buildings, and that appropriate allowances are made for the effect of the ground surface. At distances close to actual sound sources, geometric spreading does not hold. For this reason, when predicting nondetectability, it is important to make the measurement in the far field (greater than 3-5 times the major dimension of the source) where geometric spreading does take place.

Atmospheric Absorption

General

Atmospheric absorption is dependent upon distance, frequency, relative humidity, temperature and, to a very small degree, atmospheric pressure. It is caused by two phenomena. The first one, known as "classical absorption," involves the conversion of sound into heat by viscous losses and heat conduction; this produces negligible attenuation except at frequencies above 30 kHz (Embleton, 1980). The second phenomenon, "molecular absorption," produces significant attenuation at audible frequencies and is caused by the sound wave losing energy to internal vibrations of colliding oxygen and nitrogen molecules.

The loss due to vibrating oxygen molecules, through the catalytic action of water vapor, produces significant attenuation at frequencies above 2 kHz. This phenomenon has been known since the early part of the century; however what has only been known since the early 1970's is that the energy absorbed by nitrogen molecules produces attenuation at lower frequencies (Piercy, 1972; Bass, Sutherland, Piercy, & Evans, 1984). Since then a new set of molecular absorption curves has been developed and published as the "American National Standard Method for the Calculation of the Absorption of Sound by the Atmosphere" (ANSI, 1978). Tables and formulas suitable for use in a hand calculator are available in Sutherland (1975). This is a relevant factor for Army materiel which produces the major portion of its energy in the 250-500 Hz region (MIL-STD-1974 addressed only molecular absorption due to oxygen as specified in SAE Standard ARP 866 (SAE, 1964)).

Examples of the ANSI curves (Figures 4 and 5) show the "excess attenuation" (reduction of SPL in addition to that of geometric spreading) due to molecular absorption for 1 kHz and 4 kHz. These curves show that excess attenuation is highly dependent upon temperature and relative humidity, with the best propagation being caused by hot-moist (jungle) and cold-dry (arctic) conditions, and the least favorable propagation being caused by hot-dry (desert) conditions. These curves are accurate only for a uniform local atmosphere, which is rarely, if ever, found in practice. The excess attenuation will probably deviate from these values in individual situations, but the average of the excess attenuation at many sites should be close to the published values.

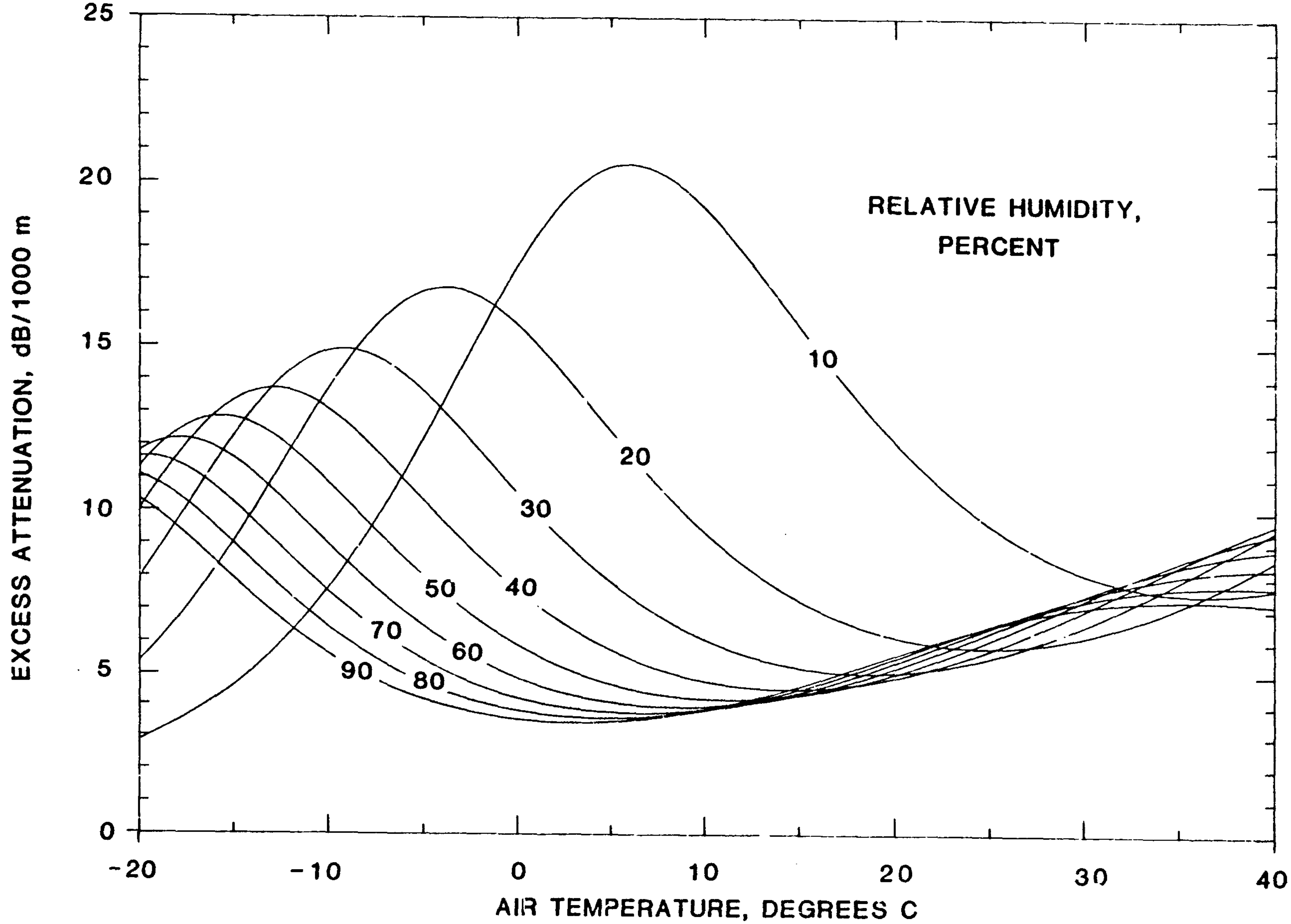


Figure 4. Excess attenuation due to molecular absorption at 1000 Hz.

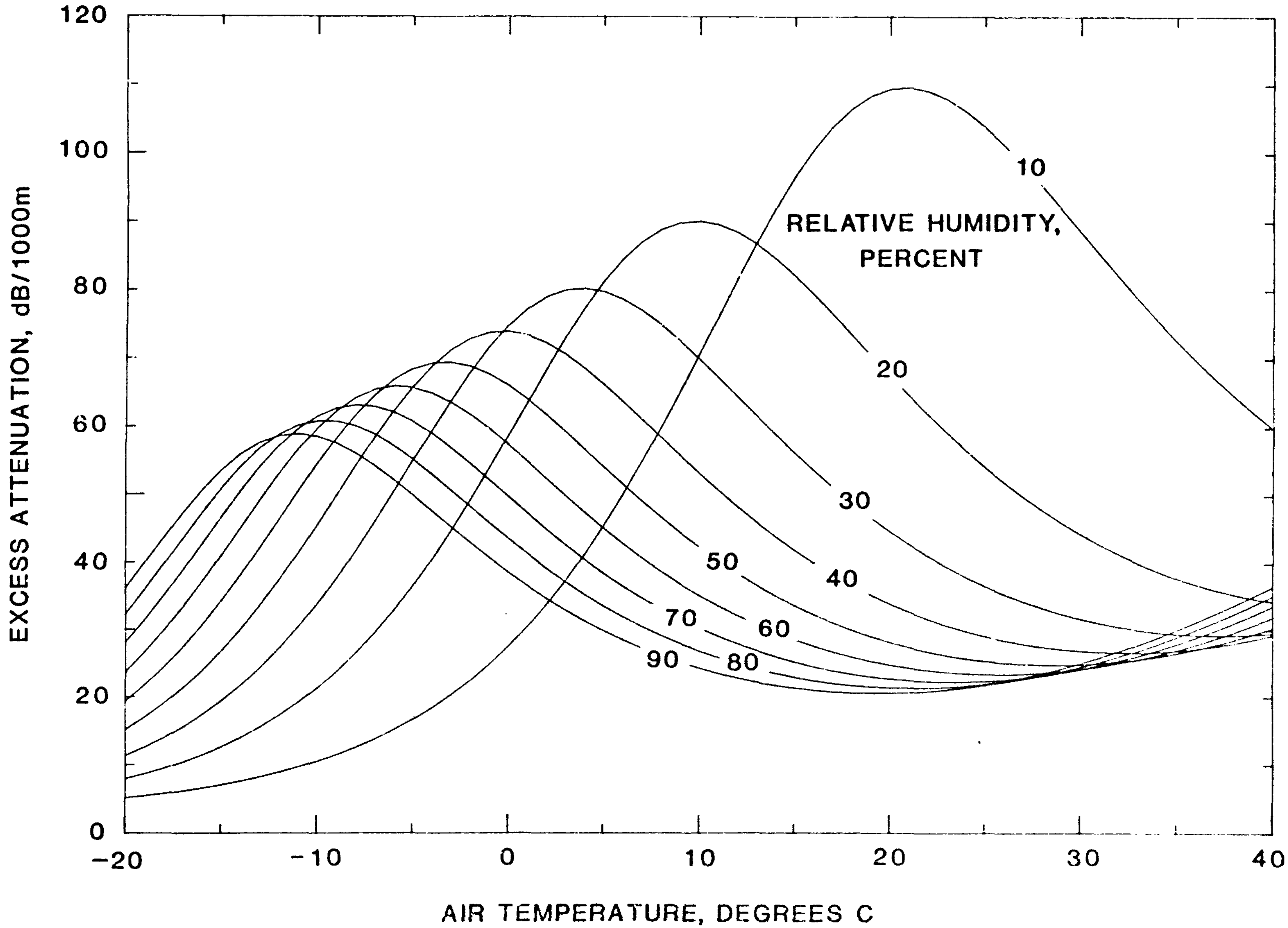


Figure 7. Excess attenuation due to molecular absorption at 4000 Hz.

Assumed Conditions

The assumed nominal conditions for determining the effect of atmospheric absorption, in accordance with ANSI S1.26, are 15° C and 70% relative humidity.

These conditions have been selected because they represent temperate zone climatic conditions and because the excess attenuation does not vary dramatically with small changes above or below these conditions. The attenuation values due to atmospheric absorption, used in this proposal, appear in Table 2. Attenuation due to both geometric spreading and atmospheric absorption is obtained by multiplying the values of this table by the propagation distance (in multiples of 1000 m) and adding this to the loss caused by geometric spreading.

Ground Effect

General

In most practical situations, sound sources and receivers are located near the ground and not in free space. When sound encounters the ground, some of it is reflected and some of it is absorbed. The reflected wave then interacts with the wave that moves directly from the source to the receiver and produces the ground effect which, under ideal conditions, can range from a doubling of pressure to complete cancellation.

During the past 15 years, a number of researchers have developed models for predicting ground effect, primarily for use around airports and highways (Delany & Bazley, 1971; Chessell, 1977; Daigle, Piercy, & Embletom 1983). This work has shown that, in addition to losses due to geometric spreading, the presence of the ground can provide up to 20 dB of attenuation in received sound pressure level in the mid-frequencies (250-500 Hz), and a 6-dB enhancement at frequencies below 100 Hz.

The essential parameters of the models are frequency, source-receiver geometry; acoustic characteristics of the ground surface; and nonhomogeneity of the atmosphere (turbulence). The geometric parameters are the source and receiver heights and the ground separation distance. The characteristic impedance of the ground is described by its flow resistivity. The effect of turbulence is described by sound level fluctuation in terms of the amplitude and phase of direct and reflected waves. The formulas used in the calculations for ground effect are covered in Appendix C.

TABLE 2

Sound Attenuation Coefficient (α) Due to Atmospheric Absorption at 15° C and 70 Percent Relative Humidity

Frequency (Hz)	Absorption Coefficient (dB/1000 m)
50	0.1
63	0.1
80	0.1
100	0.2
125	0.3
160	0.5
200	0.7
250	1.0
315	1.4
400	1.9
500	2.4
630	3.0
800	3.7
1000	4.4
1250	5.3
1600	6.8
2000	8.8
2500	11.9
3150	16.9
4000	25.1
5000	37.1
6300	56.4
8000	87.7
10000	132.7

Source and Receiver Height and Distance

Ground effect is highly dependent upon the height of the source and the receiver above the ground (Embleton, 1980) (the two can be interchanged without effect). For example, as shown in Figure 6, for a source height of 1.2 m at a propagation distance of 300 m, as receiver height increases from 0.12 to 12 m, excess attenuation decreases in amplitude from approximately 20 dB to 9 dB. If one is seeking concealment, it is important to get the most attenuation by putting the source as close as possible to the ground. The converse is also true, that is, when seeking to detect, ground effect will be minimized and detection distance increased if the listener is elevated.

Under ideal conditions, as the distance between the source and the receiver increases, excess attenuation due to the ground increases in magnitude and the affected frequency range widens (Piercy, Embleton, & Sutherland, 1977). However, in more practical situations in which the effect of turbulence is included, between 100 and 1000 m, very little change in the magnitude of the ground effect occurs, and the effect is limited to a shift to lower frequencies with increasing distance (Figure 7).

Ground Impedance

The composition and impedance of the ground surface (described by its flow resistivity) strongly affects the amplitude and phase of the reflected wave (Chessell, 1977; Delaney & Bazley, 1970; Attenborough, 1982). Characteristic values are 15 Rayls for newly fallen snow; 50 Rayls for sand; 200 Rayls for grass; 800-2500 Rayls for sandy silt packed by vehicles; and 20,000 Rayls for sealed asphalt. Figure 8 shows the variation in attenuation due to different ground surfaces for a distance of 300 m. As the ground surface gets softer (lower impedance), greater attenuation is produced and the frequency of maximum attenuation is lowered. For the purpose of the proposed nondetectability standard, it is suggested that the ground impedance for grass be used because grass is characteristic of the vast majority of surfaces on which ground forces would be operating.

Turbulence

The attenuation produced by ground effect is based upon a precise theoretical relationship between the direct and the reflected waves. Under actual field conditions, however, air is neither homogeneous nor still; large eddies are found due to thermal and wind velocity gradients near the ground. Careful measurements performed by Parkin and Scholes (1965) and Daigle and Piercy (1978) have shown that this effect, described as atmospheric turbulence, can cause fluctuation of the sound waves at the listener's location. These variations in atmospheric conditions continuously change the relationship between the direct and reflected waves thereby reducing the degree of phase cancellation ideally achievable. This

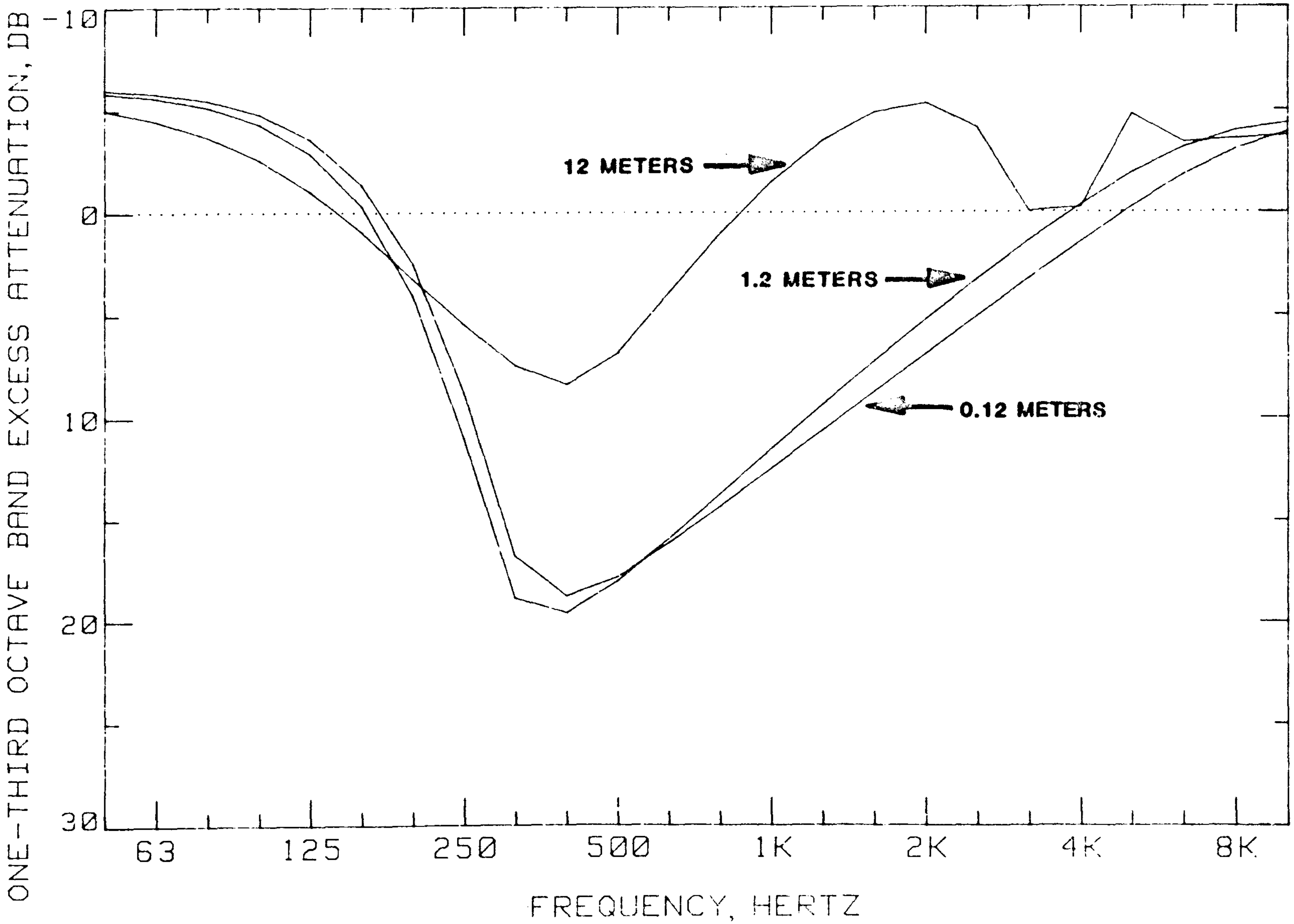


Figure 6. Ground effect with atmospheric turbulence at 500 m for a 1.2-m source height over grass for three different listener heights.

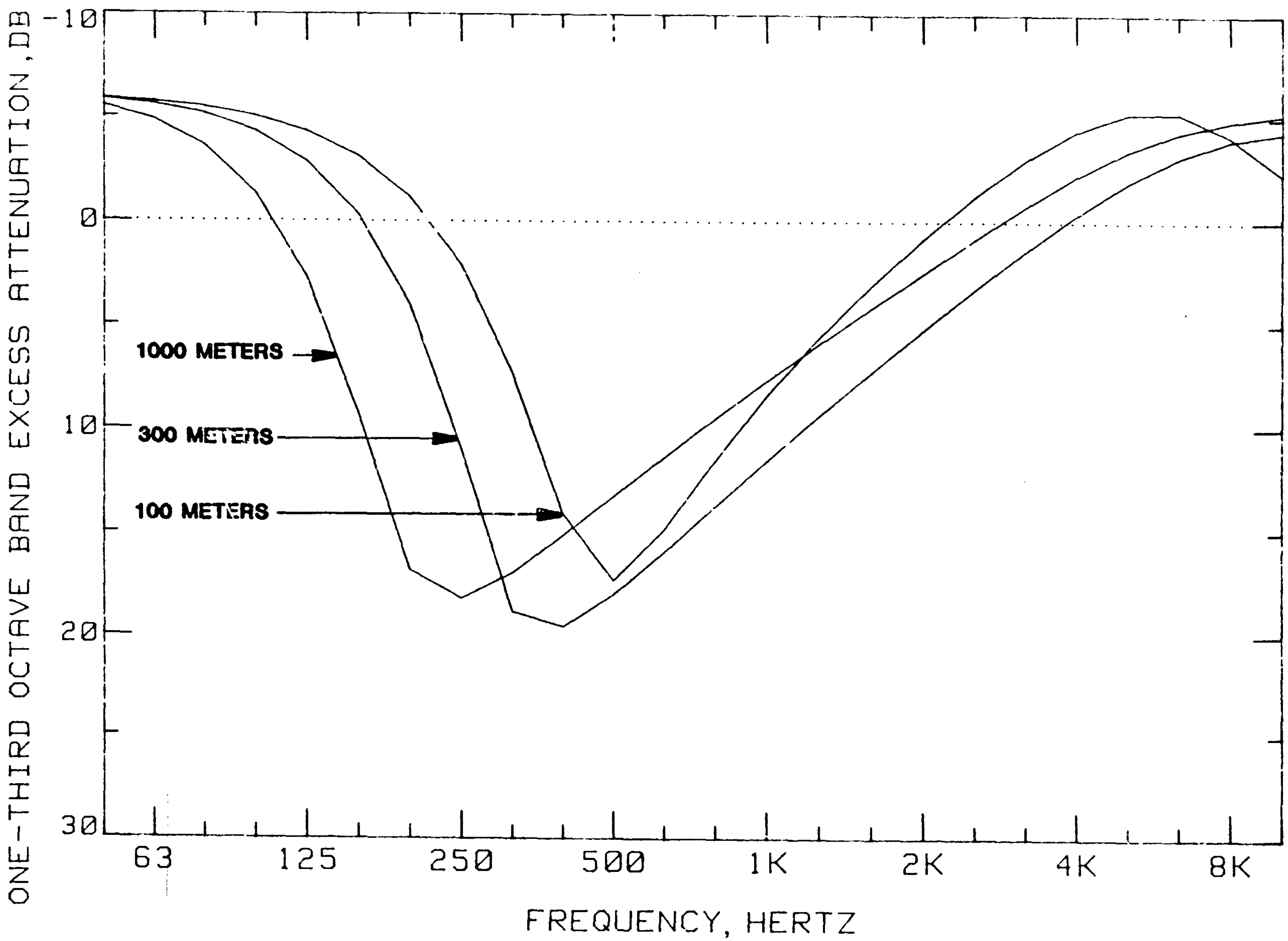


Figure 7. Ground effect with atmospheric turbulence for 1.2-m source and listener heights over grass for three different distances.

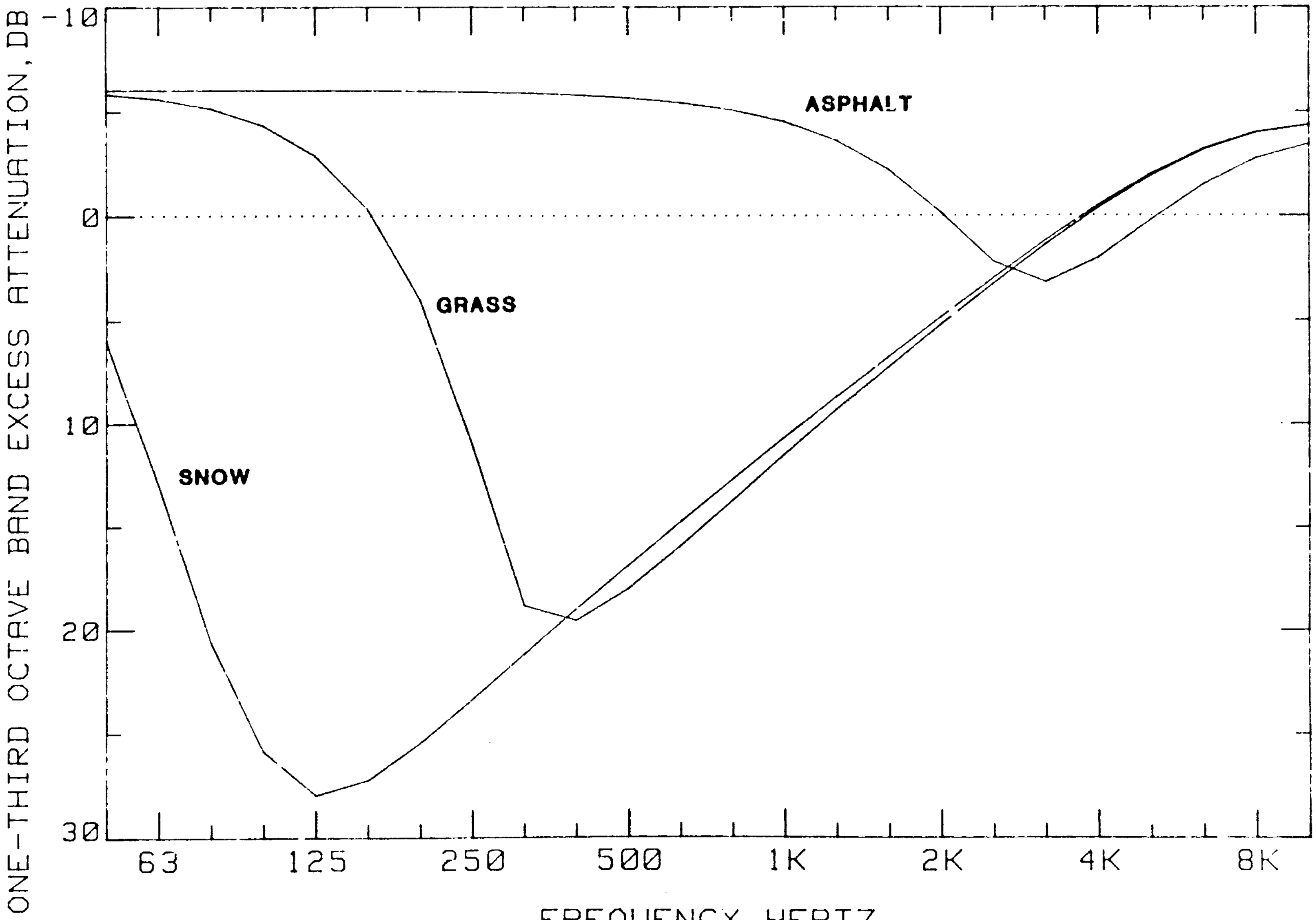


Figure 8. Ground effect with atmospheric turbulence at 300 m for 1.2-m source and listener heights over three different ground surfaces.

results in less attenuation than in a quiet atmosphere. Computations based upon coherent acoustic theory indicate that excess attenuation due to ground effect could reach 40 dB at great distances in still air; however, turbulence reduces this effect to a practical maximum value of 25 dB. Figure 9 shows the change in excess attenuation at 300 m due to turbulence. This effect is greater on a hot windy day and is smaller under nocturnal inversions (Embleton, 1980).

Measurement Surface

When computing the excess attenuation due to the ground, it is important to include the ground effect which occurs between the source and the measuring microphone, as well as that between the source and the receiver (listener). The ground effect between the source and the measurement microphone must be accounted for to establish the true source characteristics which can then be used to calculate propagation effects. For this reason, it is important, particularly in a military standard, to specify the surface over which measurements are to be made, the source and microphone heights, and the assumed receiver height.

Assumed Conditions

Based on the preceding, the following assumptions are made. The ground surface will be grass (flow resistivity of 200 Rayls). The turbulence is that which exists under calm, neutral atmospheric conditions as given by a fluctuating index of refraction $\langle\mu^2\rangle = 0.6 \times 10^{-6}$. The source and listener heights will be 1.2 m. The measurement microphone shall be placed above a flat level grass surface at a height of 1.2 m; this height was chosen because it is the one standardized upon by the Society of Automotive Engineers (SAE, 1978).

Inclusion of ground effect will have a major influence on the noise limits in the 250-500 Hz region, so its impact in raising the allowable level will be considerable; this influence (up to 20 dB) is most pronounced when the listener and the noise source are close to the ground. If either the listener or the source is elevated, such as on a hillside or in a tree, the majority of the ground effect will be eliminated. Also, if the surface is acoustically harder than grass (e.g., hard-packed clay, asphalt, or water), the ground effect will be reduced in magnitude and also raised to a higher frequency where it will be less beneficial.

Refraction Due to Wind and Temperature Gradients

General

Wind and temperature gradients produce refraction or bending of sound rays which affect the propagation of sound. This effect usually occurs for distances greater than 50 m.

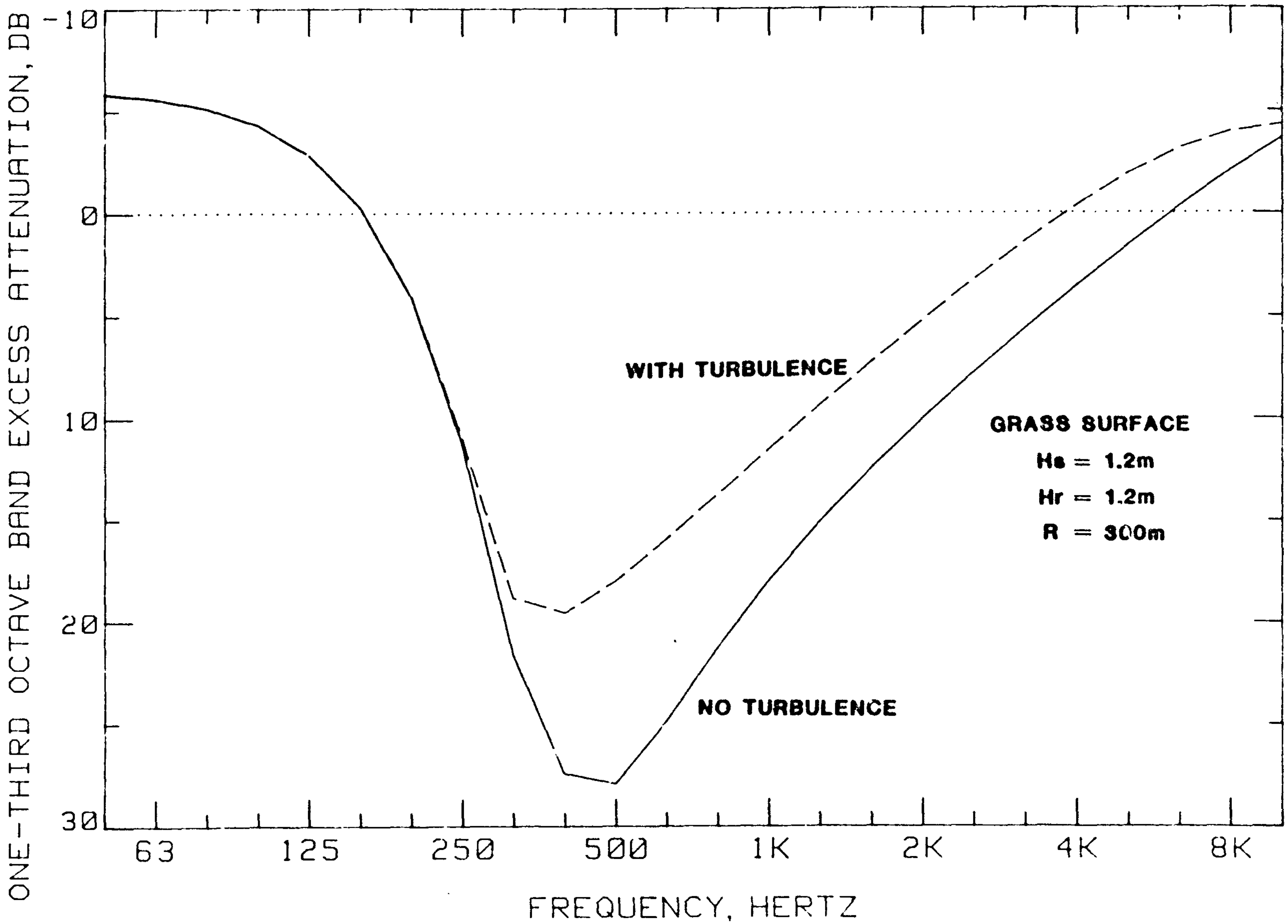


Figure 9. Effect of turbulence on reducing excess attenuation due to ground effect.

Sound travels faster in warmer air; therefore, where a temperature gradient is present, parts of the wave front move at differing velocities which results in a bending of the "rays" of sound. Enhanced propagation may result if temperature increases with height above the ground (inversion condition) by causing the sound rays to bend downward. Likewise, wind velocity normally increases with height. Therefore, if the sound is traveling with the wind, the higher wind velocity at higher altitudes bends the sound waves toward the ground. Both of these conditions can cause sound to propagate more easily at long distances by canceling a portion of the excess attenuation due to ground effect. This enhancement is usually limited to about 3 dB (Parkin & Scholes, 1965; Embleton, Piercy, & Olson, 1976).

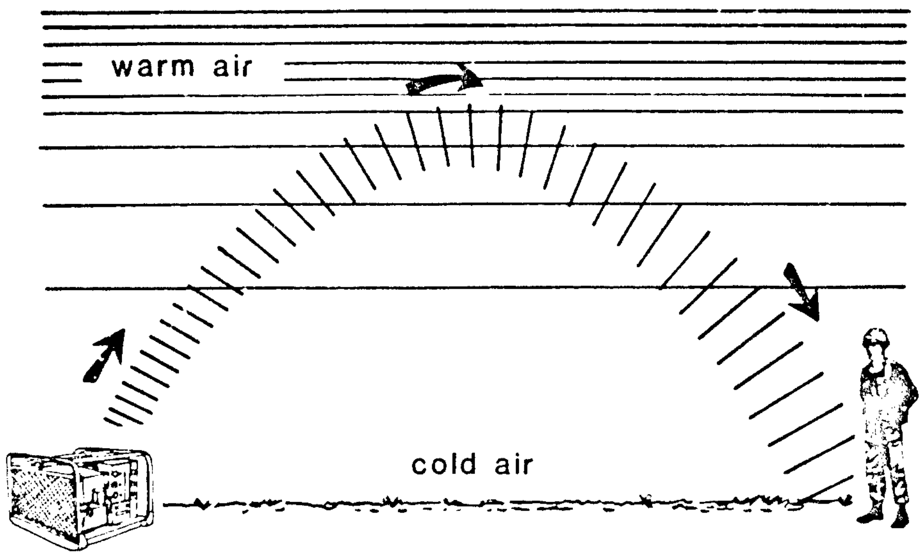
Alternatively, if the temperature gradient is negative (lapse condition) or if the sound propagates into the wind, the sound bends upward leaving a sound shadow zone. This shadow zone greatly reduces the ability of sound waves to propagate. Excess attenuation due to this shadow zone may reach 25 dB at distances as close as 200 m and at frequencies around 500 Hz, with less attenuation resulting at higher and lower frequencies and at shorter distances (Fidell & Bishop, 1974; Piercy, Embleton, & Sutherland, 1977). The effect of refraction due to temperature gradients during daytime and nighttime conditions is graphically depicted in Figure 10. Zero temperature gradients and cross winds are comparable to netural windless conditions.

Daytime Effect

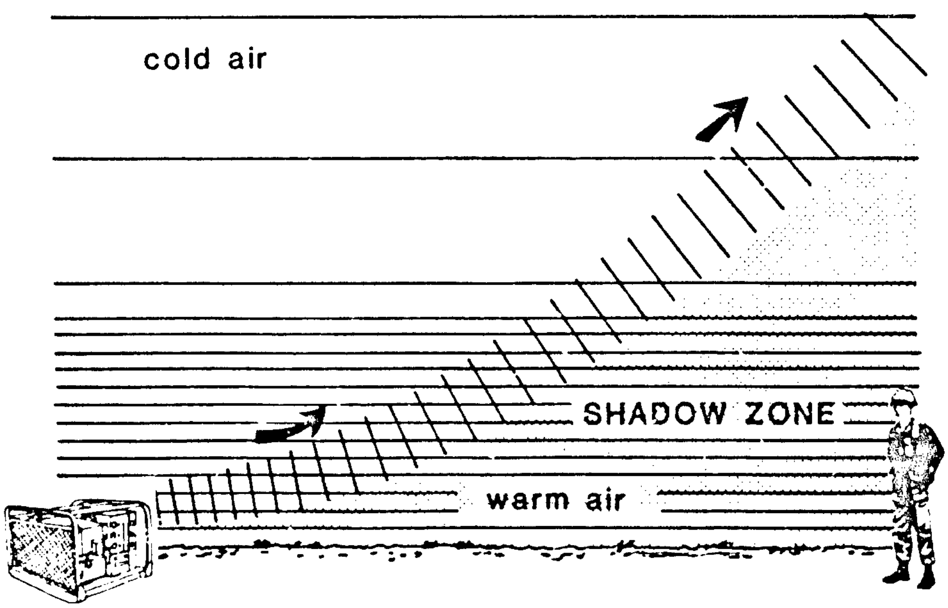
Refraction due to wind and temperature gradients during the day may cause a shadow zone to occur which produces excess attenuation at the low frequencies characteristic of Army materiel. This excess attenuation, which may be as much as 25 dB, will significantly reduce detectability compared to neutral conditions. Neutral conditions are usually present during the early evening (Raspet, 1984). In addition, daytime windy conditions may cause foliage to rustle, raising the ambient noise level and thereby further decreasing the detectability distance. It should be obvious, therefore, that most daytime conditions lead to a prediction of reduced detectability distance for materiel (compared to nighttime).

Nighttime Effect

At night, temperatures are typically lower near the ground, and sound rays are bent downward with a resultant decrease of up to 3 dB in the attenuation provided by the ground effect. Wind velocities tend to be lower at night, reducing the possibility of a shadow zone due to wind and reducing the noise caused by rustling leaves. Moreover, background noise levels may be up to 10 dB lower at night due to reduced manmade noise. The combination of these effects of refraction and lowered background noise explains the fact that during nighttime conditions sound can be heard at significantly greater distances than during the day.



<u>DOWNWARD</u> REFRACTION OF SOUND WAVES AT NIGHT DUE TO HIGHER VELOCITY OF SOUND WAVES IN WARM UPPER AIR



<u>UPWARD</u> REFRACTION OF SOUND WAVES, PRODUCING A SHADOW ZONE DURING THE DAY, DUE TO HIGHER VELOCITY OF SOUND WAVES IN WARM LOWER AIR

Figure 10. Effect of refraction due to temperature gradients during nighttime and daytime conditions.

Assumed Conditons

For the proposed limit, neutral wind and temperature conditions are assumed. This means that during the day, materiel will probably be much less detectable than predicted by the limit (the SPL at the listener may be up to 25 dB below the level for nondetectability). During nighttime, materiel may be slightly more detectable than predicted by the limit (the SPL at the listener may be up to 3 dB above the level for nondetectability).

Barriers

General

Walls, berms, solid fences, vehicles, shelters, a stack of sandbags, or any reasonably solid body which blocks the line of sight between the noise source and the listener can provide significant attenuation (up to 25 dB). The degree of attenuations is dependent upon the relative locations of the noise source, the barrier, and the listener, as illustrated in Figure 11. The diffraction angle, α, should be as large as possible (preferably greater than 30°) for the barrier to be effective. As a general rule, the greatest attenuation is obtained when either the source or the listener is close to the barrier. Barriers provide the least attenuation at low frequencies where the long wavelengths diffract more readily around the edges of the barrier.

A barrier does not have to be massive to provide acceptable attenuation since in most cases the weakest path permits sound to diffract around the barrier, rather than travel through it. In most cases, depending upon the height and width of the barrier, the attenuation qualities of the material do not have to be great. Experience has shown that surface densities of about 2 lb/ft^2 are usually adequate. The width of a barrier must be such that the noise source is as far from the left and right edges as it is from the top. As a practical example, either a stack of sandbags or a 1/2-inch plywood barrier, which extends 1 m above the imaginary line between the top of the source and the listener and which is located 1 m from the source, would provide a minimum attenuation of 10 dB at 250 Hz and 15 dB at 2 kHz at any distance from the barrier.

Computation of Barrier Attenuation

Computation of the attenuation provided by a barrier may be made using the theory of Maekawa (1965). This computation is dependent upon the Fresnel number, N, as follows:

$$N = 2(A + B - d) / \lambda \qquad (1)$$

where:

λ = the wavelength of sound, meters

d = the straight line distance between source and receiver, meters

$A + B$ = the path distance over the wall between source and receiver, meters

Attenuation is then obtained by use of Figure 11. Even when the listener can just see the source over the barrier ($d = A + B$), excess attenuation is 5 dB at all frequencies since the Fresnel number approaches zero.

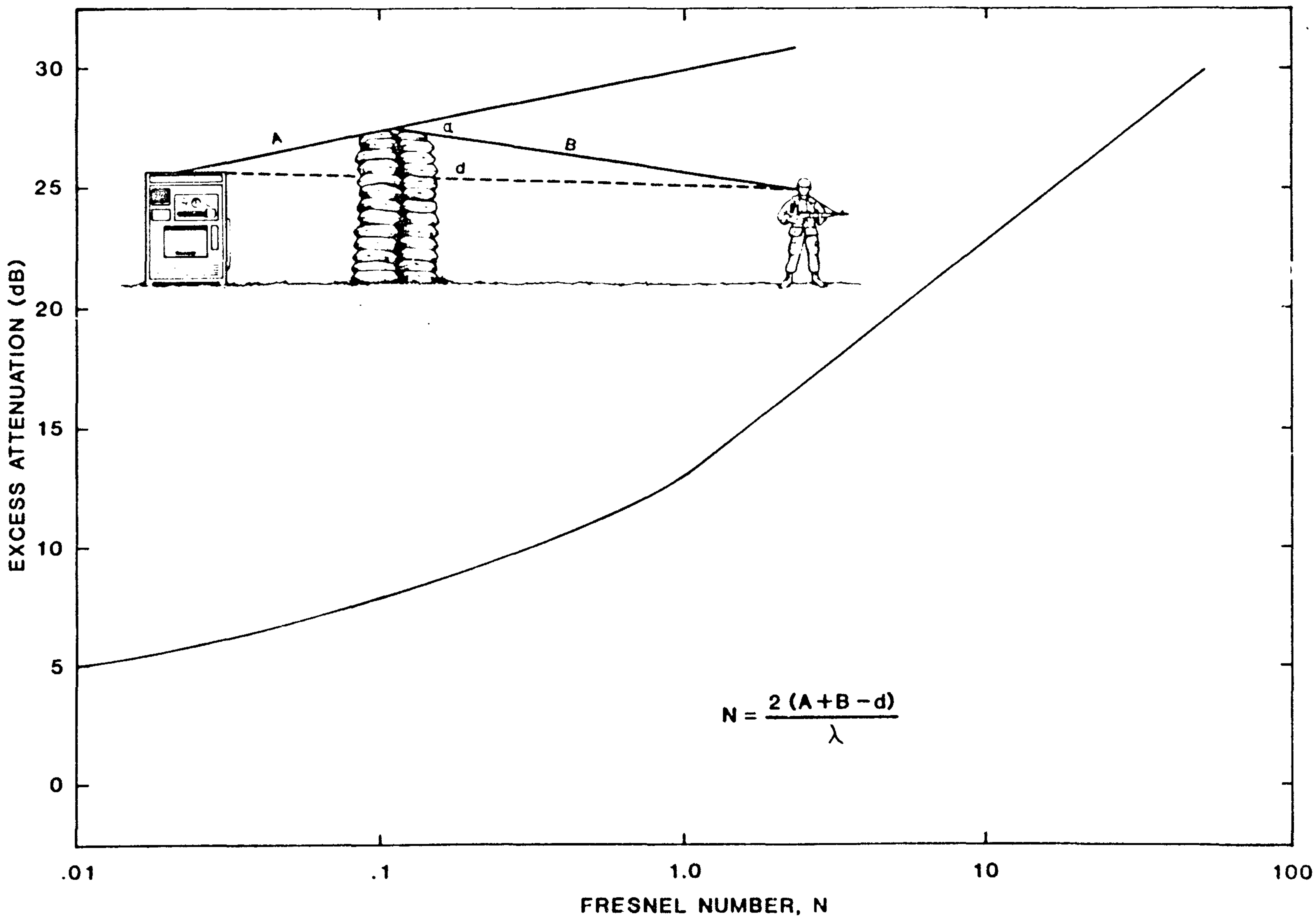


Figure 11. Excess attenuation due to a barrier as a function of Fresnel number.

Assumed Conditions

For the proposed revision of MIL-STD-1474, however, it is assumed that barriers will not ordinarily be present in field situations and the effect of barriers is excluded.

Foliage

General

The attenuation provided by shrubs and trees is usually minimal. To provide significant attenuation, foliage must be very dense, have large leaves, and have great depth. Foliage through which one can see for a considerable distance provides negligible attenuation.

Investigations by Aylor (1972) indicate that sound attenuation by plants is controlled mainly by scattering of the sound wave due to the foliage and by changes in the ground effect due to the root structure. Scattering of the sound wave, which is the dominant mechanism for attenuation produced by foliage is dependent upon leaf density and the width of the leaves. The effect is greatest at frequencies above 2000 Hz, reaching a maximum of 20 dB. Even at long distances there is very little attenuation below 500 Hz.

Typical Attenuation Values for Foliage

Typical excess attenuation due to a dense hardwood brush foliage with an average leaf width of 5 cm and a leaf area per unit volume of 0.5/m is given in Table 3.

TABLE 3

Typical Excess Attenuation (dB) Due to Foliage
(Data from Aylor, 1972)

Depth of foliage (meters)	Frequency (Hz) 500	1000	2000	4000	8000
10	0.9	2.1	3.8	5.8	6.4
50	2.0	4.8	8.5	13.0	14.3
100	2.8	6.7	12.0	18.4	20.2

The values shown in this table are somewhat lower than those shown elsewhere for forests and jungles (Dobbins & Kindick, 1966; Eyring, 1946). This is because for Aylor's data, the ground effect has been excluded, while it was included with prior foliage data. These values should not be extrapolated to greater distances because attenuation appears to be limited to the values shown.

Assumed Conditions

Foliage will be assumed to be sparse or absent in typical field situations, and the effect of foliage will therefore be excluded for the proposed limit.

SUMMARY LISTING OF INCLUDED AND EXCLUDED NONDETECTABILITY PARAMETERS

The previous section of this report discussed all the presently known factors which affect propagation of sound and a person's ability to detect sound. Those factors which are recommended for inclusion in a practical nondetectability model are:

Geometric spreading.
Atmospheric absorption.
Background noise.
Ground effect with atmospheric turbulence.
Listener's threshold of hearing and presumed efficiency.

On the other hand, there are a number of factors which should not be included because they probably will not exist in a majority of operational situations. The factors that should be excluded are:

Barriers.
Foliage.
Refraction due to wind.
Refraction due to air temperature.
Intermittency and pure tone corrections.

PROPOSED NONDETECTABILITY LIMITS

Computation of the Limits

The limits for conformance to the standard were determined, in 1/3-octave bands, by establishing the levels not to be exceeded for nondetectability at the listener's location.

These levels were determined by first assuming that nondetectability is provided by setting the signal level of the materiel just equal to the background noise level (0 dB S/N ratio) for each 1/3-octave band. To account for low frequency masking, this spectrum was then converted to an auditory filter band spectrum using the procedure of Fidell and Horonjeff (1980), as shown in Appendix D. The auditory filter spectrum was then modified by signal detection theory to produce 50 percent detection with a 1 percent false alarm rate by using the following equation:

$$L'_2 = L_A + 10 \log_{10}(d' / (\eta W^{1/2})) \tag{2}$$

where:

L_A = auditory filter band level, dB

d' = 2.32

η = assumed listener efficiency of 0.4

W = effective auditory filter bandwidth, Hz

If L'_2 was less that the threshold of hearing (ISO R-226) for any band, L'_2 was replaced by that threshold value. A noise source was considered to be inaudible if it did not exceed either value in any band, as follows

$$L_2 = \max (L'_2 , L_{\text{ISO Threshold}}) \tag{3}$$

This not-to-be-exceeded level was then transferred back to the measurement location by considering geometric spreading, atmospheric absorption, and the ground effect (including turbulence). The level not to be exceeded at the measurement location was calculated for each 1/3-octave band from the following equation:

$$L_1 = L_2 + 20 \log_{10}(r_2/r_1) + \alpha(r_2 - r_1) + A_{ge}(r_2) - A_{ge}(r_1) \quad (4)$$

where:

L_1 = the SPL at the measurement location, in dB

L_2 = the SPL at the listener's location producing nondetectability for that band, in dB (see Eq. 2)

r_1 and r_2 = the distances from the noise source to the measurement location, and to the nondetectability distance, respectively, in meters

α = the sound attenuation coefficient due to atmospheric absorption, in dB/meter

$A_{ge}(r_2)$ = the excess attenuation due to ground effect between the source and the nondetectability location, in dB

$A_{ge}(r_1)$ = the excess attenuation due to ground effect between the source and the measurement location, in dB

See Appendix C for the computation of A_{ge}.

Using the levels computed with this procedure, it is proposed that aural nondetectability limits be divided into two categories as described below:

Limit for Critical Aural Nondetectability

This limit assumes that the listener is in the quietest background noise levels which are likely to be encountered in practice, and that the closest highway and community noise sources are further than 16 km away. It provides aural nondetectability under most conditions of wind, temperature, time of day, ground surface, and height above ground.

Limit for Typical Aural Nondetectability

This limit assumes that the listener is in a quiet rural area, and that the closest highway and community noise sources are further than 4 km away. It provides aural nondetectability under many but not all conditions of wind, temperature, time of day, ground surface, and height above ground.

The actual limits are shown in Tables 4 and 5; they show the 1/3-octave band levels that are not to be exceeded at the measurement distance specified for various nondetectability distances. These tabular data are also shown in graphical form in Appendix A.

TABLE 4

Critical Aural Nondetectability Limits (dB)

1/3 Octave Band Frequency (Hz)	Nondetectability Distance (m)																				
	10	20	30	100	200	300	400	500	750	1000	1250	1500	2000	3000	4000	1000	2000	3000	4000	5000	6000
50	53	59	62	61	68	71	74	68	71	74	76	78	81	85	88	68	75	79	82	85	88
63	46	52	56	55	61	65	68	62	66	69	71	73	76	81	85	63	70	75	79	83	86
80	39	45	49	50	56	60	62	57	61	64	67	69	73	79	84	57	67	73	78	83	87
100	3	38	42	45	51	55	58	53	58	61	64	67	72	80	86	55	66	74	80	86	88
125	25	31	34	41	48	52	55	50	56	61	65	68	74	83	87	54	68	77	81	83	85
160	21	27	30	37	45	50	54	50	57	63	68	72	77	81	83	57	70	74	77	79	80
200	25	30	34	35	44	50	55	52	62	67	69	71	74	77	79	60	67	70	72	74	75
250	28	33	36	34	45	53	59	57	62	64	66	67	69	72	74	57	62	64	67	69	71
315	30	34	38	34	47	55	59	54	57	59	60	61	63	67	69	50	55	58	61	64	66
400	27	29	34	35	46	50	52	48	50	52	54	55	57	61	64	42	47	51	55	58	60
500	26	33	38	38	46	49	50	42	44	46	48	49	52	56	60	35	41	45	49	52	56
630	22	33	38	40	48	51	53	40	43	45	47	48	51	56	61	34	41	46	50	54	58
800	16	26	32	39	48	51	53	42	45	47	49	51	54	60	65	36	43	49	54	59	64
1000	15	23	28	36	45	49	52	43	46	49	51	53	57	63	69	38	46	53	59	64	70
1250	19	21	26	30	40	44	47	43	47	50	52	54	59	66	73	40	49	56	63	70	76
1600	19	20	24	24	35	39	42	42	46	49	52	55	60	69	77	41	51	60	69	77	85
2000	13	21	21	25	36	41	44	39	44	48	51	54	60	72	82	41	54	65	75	86	96
2500	15	25	20	17	28	33	37	34	39	44	48	52	60	74	88	42	57	72	86	99	NA
3150	9	15	22	17	28	34	38	26	32	38	44	49	59	79	98	43	64	83	NA	NA	NA
4000	10	14	23	15	26	33	38	36	45	53	61	68	83	NA	NA	48	77	NA	NA	NA	NA
5000	13	21	20	18	30	38	44	44	56	67	77	88	NA	NA	NA	56	98	NA	NA	NA	NA
6300	20	25	30	27	40	50	58	55	72	88	NA	NA	NA	NA	NA	76	NA	NA	NA	NA	NA
8000	30	35	39	40	54	67	78	81	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10,000	31	37	42	47	64	81	96	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Measurement Distance (m)	2	2	2	10	10	10	10	25	25	25	25	25	25	25	25	50	50	50	50	50	50

TABLE 5

Typical Aural Nondetectability Limits (dB)

1/3-Octave Band Frequency (Hz)	Nondetectability distance (m) 10	20	30	100	200	300	400	500	750	1000	1250	1500	2000	3000	4000	1000	2000	3000	4000	5000	6000
50	53	59	62	61	68	71	74	68	71	74	76	78	81	85	88	68	75	79	82	85	88
63	50	56	59	59	65	69	71	65	69	72	74	76	80	85	89	66	74	79	83	86	89
80	49	55	58	60	66	69	72	67	71	74	76	79	83	89	94	68	77	83	88	93	97
100	46	52	56	59	65	69	72	67	71	75	78	81	86	94	100	69	80	88	94	99	102
125	41	47	51	58	64	69	72	67	73	77	81	85	91	100	104	71	85	94	98	100	102
160	39	44	48	55	63	68	72	68	75	81	86	90	94	99	101	74	88	92	95	96	98
200	42	47	51	52	61	67	72	69	79	84	86	88	91	94	96	77	84	87	89	91	92
250	44	49	53	50	61	69	76	73	78	80	82	83	85	88	90	73	78	81	83	85	87
315	46	50	54	50	63	71	75	70	73	75	76	77	79	83	85	66	71	74	77	80	82
400	43	45	50	51	62	66	68	64	66	68	70	71	73	77	80	58	63	67	71	74	76
500	42	49	54	54	61	64	66	58	60	62	64	65	68	72	76	51	56	61	65	68	71
630	37	48	54	55	63	67	68	56	58	60	62	64	67	72	76	50	56	61	66	70	74
800	31	41	47	54	63	66	68	57	59	62	64	66	69	74	80	51	58	64	69	74	79
1000	29	37	42	50	59	63	65	57	60	62	64	67	70	77	83	52	60	66	72	78	83
1250	31	34	39	42	52	57	59	56	59	62	65	67	71	79	85	52	61	69	76	82	89
1600	31	32	35	36	46	51	54	53	57	61	63	66	71	80	89	52	62	71	80	88	96
2000	25	32	32	36	47	52	55	51	55	59	63	66	72	83	93	53	65	76	87	97	NA
2500	26	26	31	28	39	44	48	45	50	55	59	63	71	85	99	53	68	83	97	NA	NA
3150	21	27	34	29	40	46	40	37	44	50	56	61	71	91	NA	55	76	95	NA	NA	NA
4000	21	25	34	25	37	44	49	47	56	64	72	79	93	NA	NA	58	88	NA	NA	NA	NA
5000	18	27	25	23	35	43	50	49	61	72	83	93	NA	NA	NA	62	NA	NA	NA	NA	NA
6300	20	25	30	27	40	50	58	55	72	88	NA	NA	NA	NA	NA	76	NA	NA	NA	NA	NA
8000	30	35	39	40	54	67	78	81	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10,000	31	37	42	47	64	81	96	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Measurement Distance (m)	2	2	2	10	10	10	10	25	25	25	25	25	25	25	25	50	50	50	50	50	50

MEASUREMENT PROCEDURE FOR DETERMINING CONFORMANCE TO THE PROPOSED LIMITS

General

To enable accurate measurement of the source for calculating nondetectability distances, the measurement was set relatively close to the test item. The specified measurement locations are in the free field for most situations (more than 3-5 times the major dimension of the test item), yet close enough to satisfy the requirement for measurement purposes of providing a 10 dB signal-to-noise ratio in each 1/3-octave band at most test sites.

Measurement Procedure

For compliance to the limits, 1/3-octave band measurements shall be made at a height of 1.2 m at the specified measurement distance over a flat, level grass surface, free of ice, snow, or vegetation over 150 mm tall. The limits shall not be exceeded on any azimuth at any frequency. When appropriate, tests may be conducted in either an anechoic or semianechoic chamber. The equipment shall be evaluated under those conditions for which nondetectability is required, as specified.

Measurement values shall be the maximum meter deflection using the fast exponential-time-averaging characteristics of a sound level meter, or equivalent, (125-ms time constant) to approximate the 200-ms integration time of the human ear. Instrumentation shall meet the appropriate ANSI requirements as specified.

Measurements made under other conditions will invalidate the assumptions used for computing the ground effect and, in turn, invalidate the limiting values specified for the military standard.

CONCLUDING REMARK

Following the references there are four appendixes. Appendix A presents the aural nondetectability limits (Tables 4 and 5) in graphical form. Appendix B summarizes the factors which facilitate or impede sound propagation. This information may assist users in assessing the effect of their particular tactical situation on the detectability of their equipment. Appendix C makes a detailed presentation of the method of computing excess attenuation due to ground effect. Appendix D summarizes the procedure for converting a sound spectrum into an auditory filter band spectrum.

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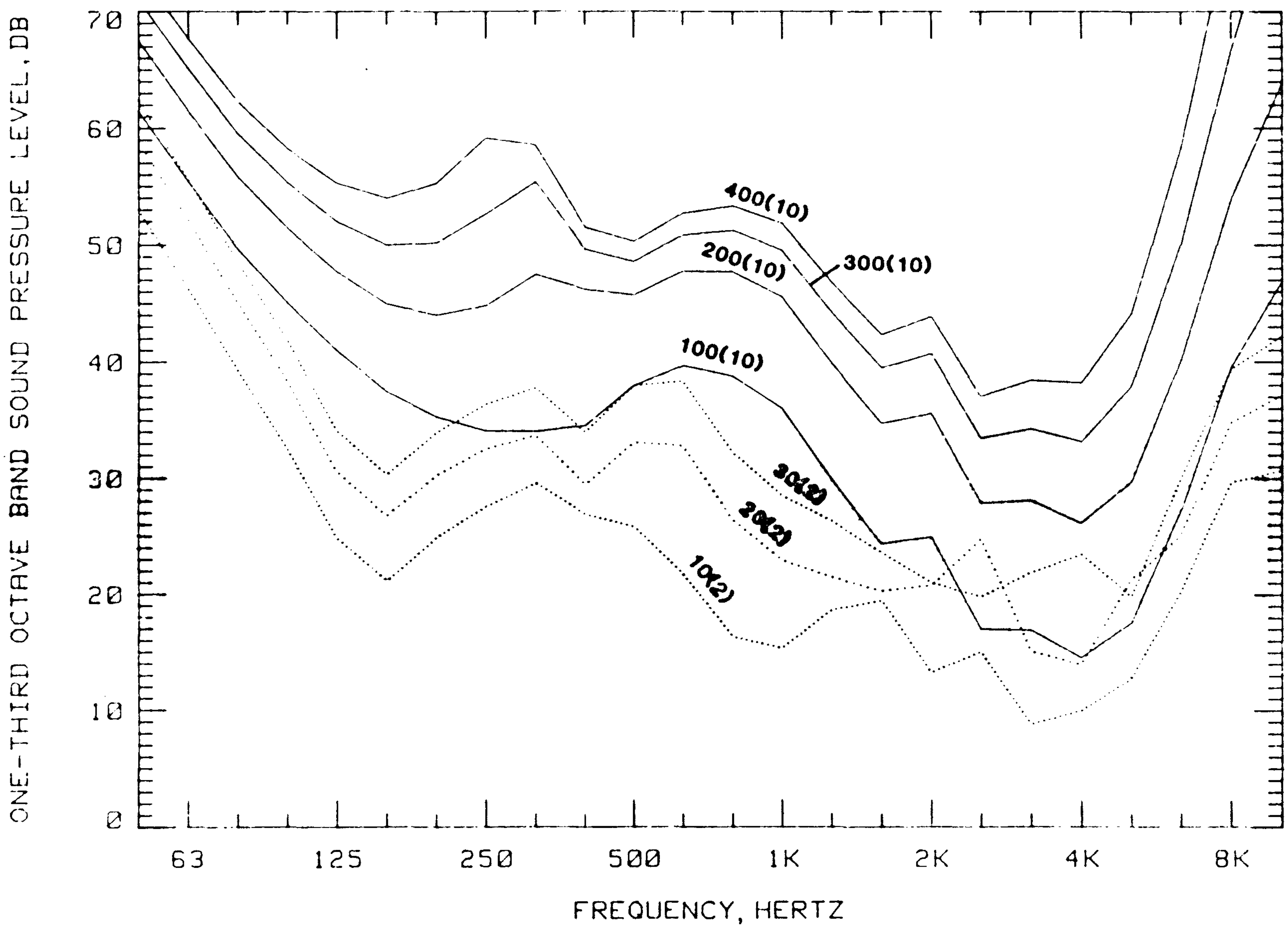
APPENDIX A

NONDETECTABILITY LIMITS PRESENTED IN GRAPHICAL FORM

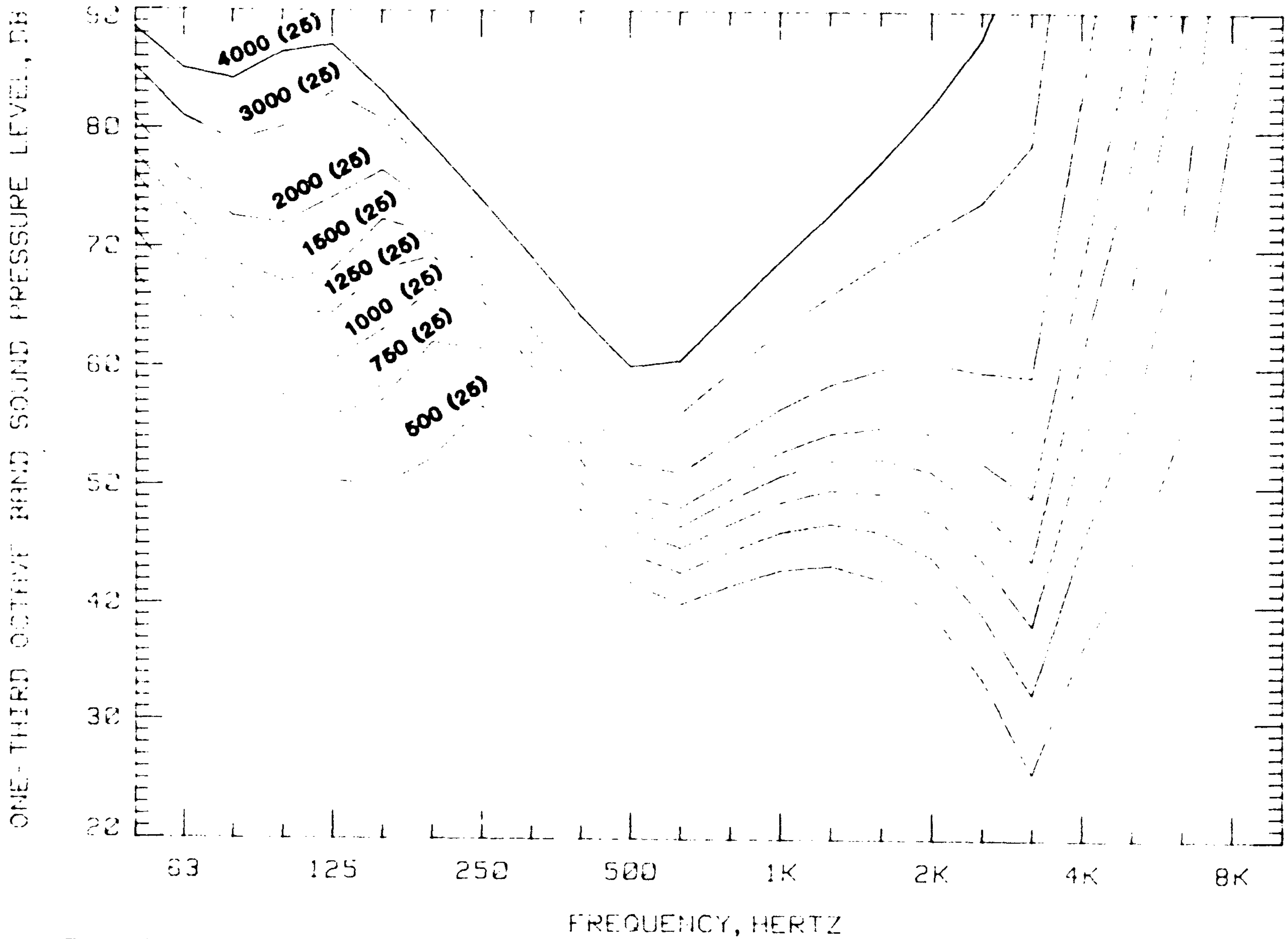
NONDETECTABILITY LIMITS PRESENTED IN GRAPHICAL FORM

In addition to the presentation of the limits in tabular form, this appendix presents them in graphical form. Such a presentation has two advantages. First, it provides the user with the general shape of the limit, graphically indicating those frequencies where noise reduction is most important for minimizing detection. Second, it permits the plotting of the materiel noise level directly on the figure, thereby determining that frequency which produces detectability, the number of decibels by which the limit is exceeded, and an approximation of the nondetectability distance. (Obviously this applies only to measurements made at the same distance as those specified in the figure.) The limits, for both critical and typical aural nondetectability, are shown in Figures 1A through 6A.



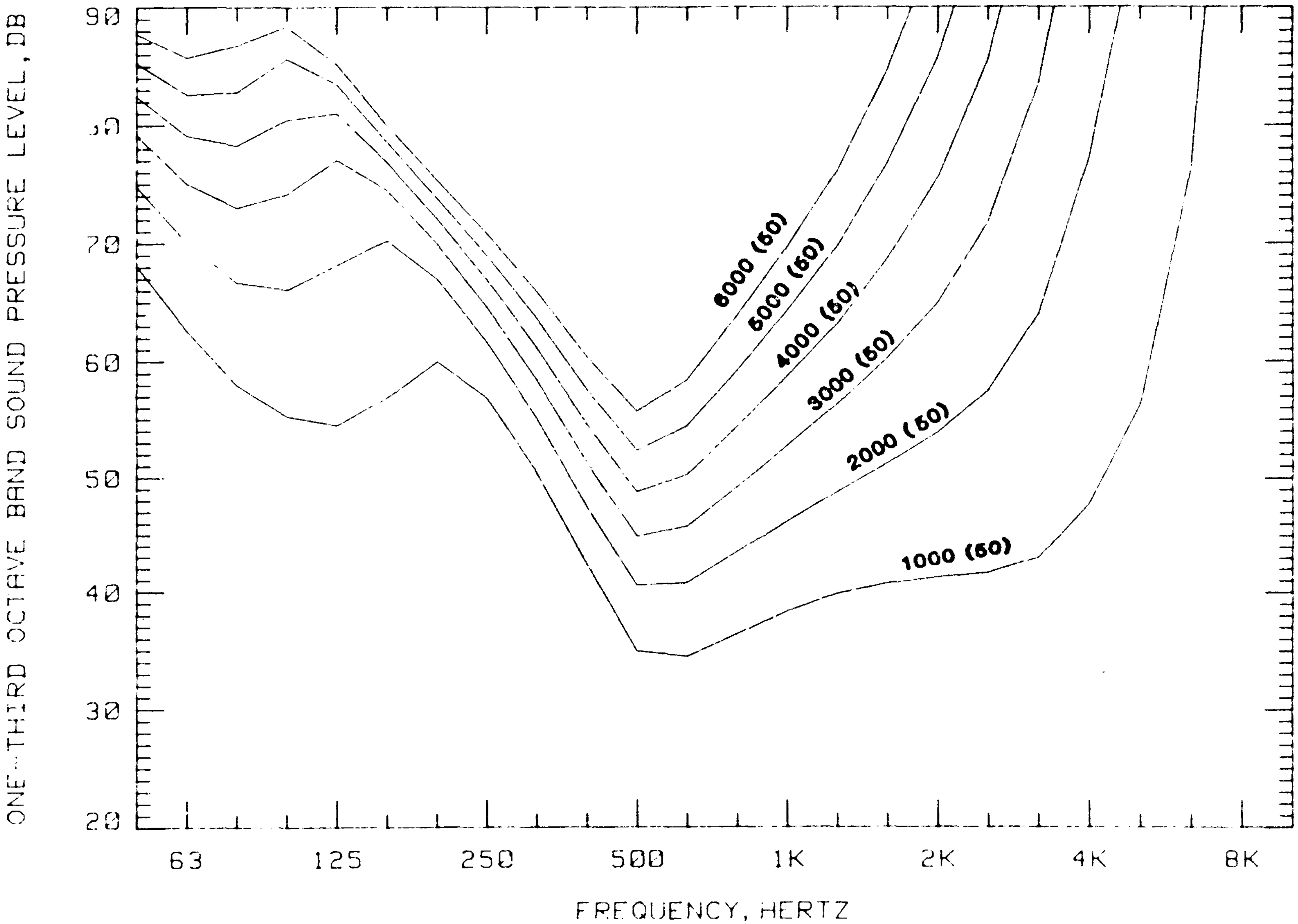
Note: The number in parentheses is the measurement distance in meters.

Figure 1A. Critical nondetectability limits for 10-400 meters.



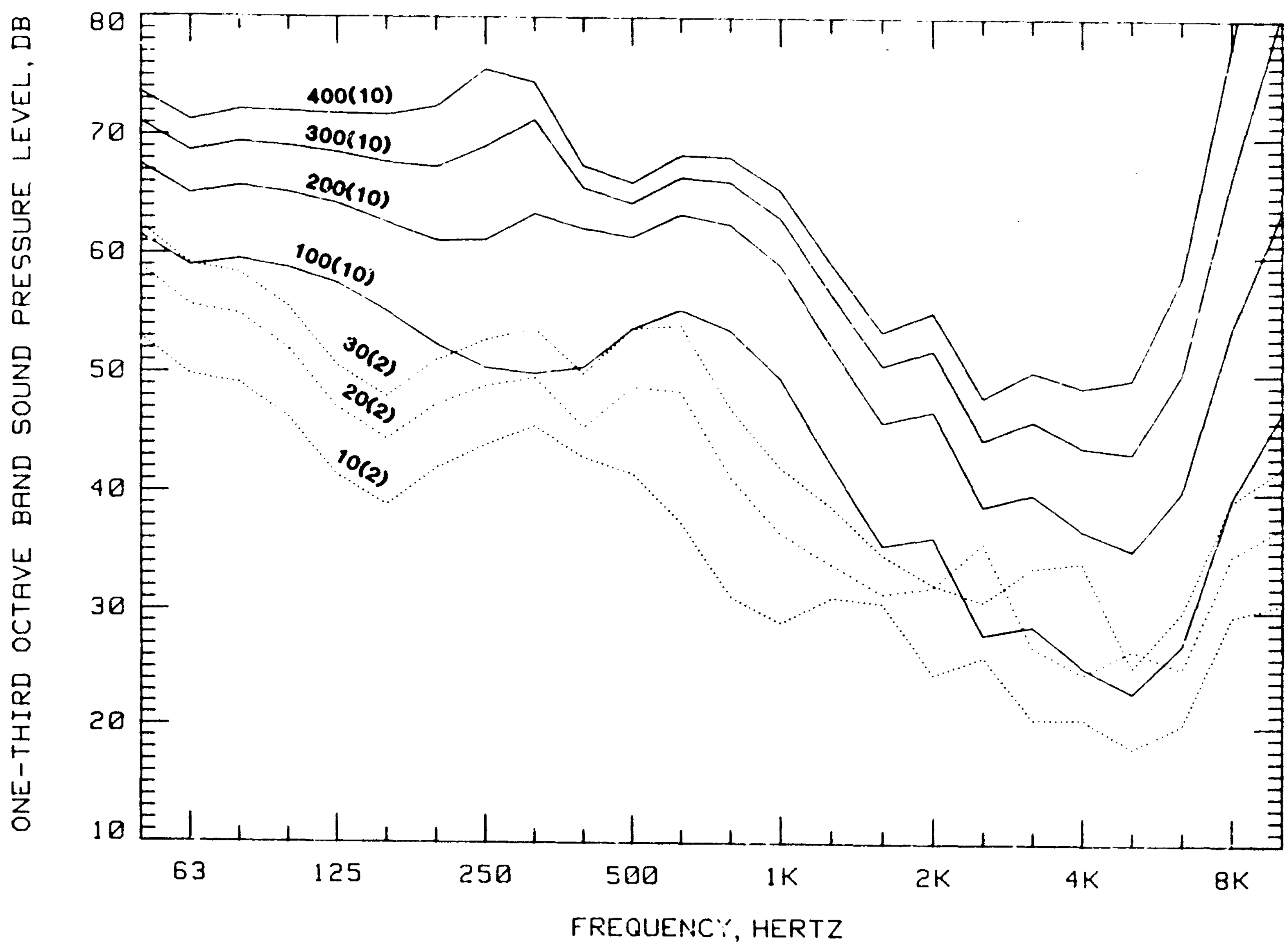
Note: The number in parentheses is the measurement distance in meters.

Figure 2A. Critical nondetectability limits for 500-4000 meters.



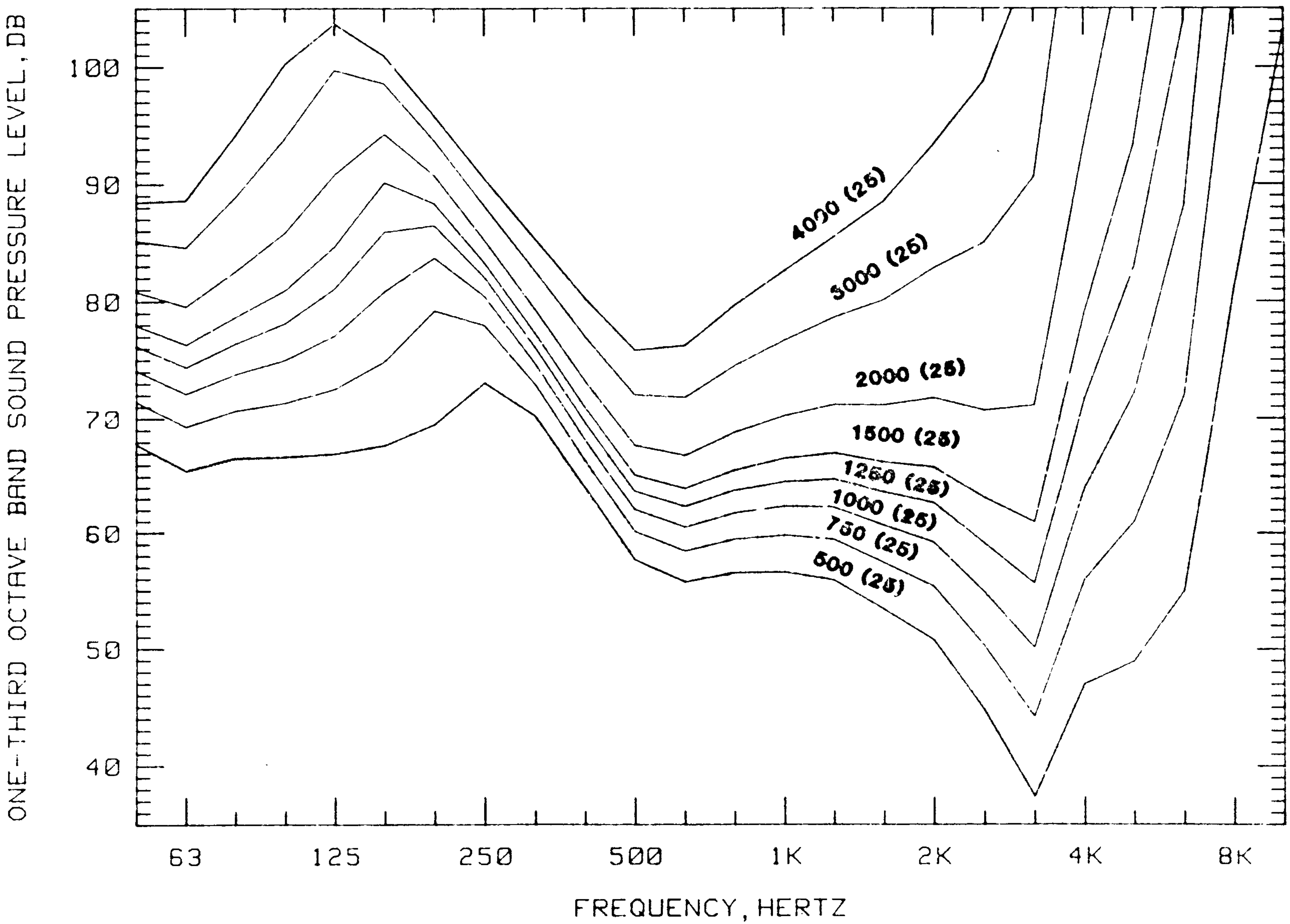
Note: The number in parentheses is the measurement distance in meters.

Figure 3A. Critical nondetectability limits for 1000-6000 meters.



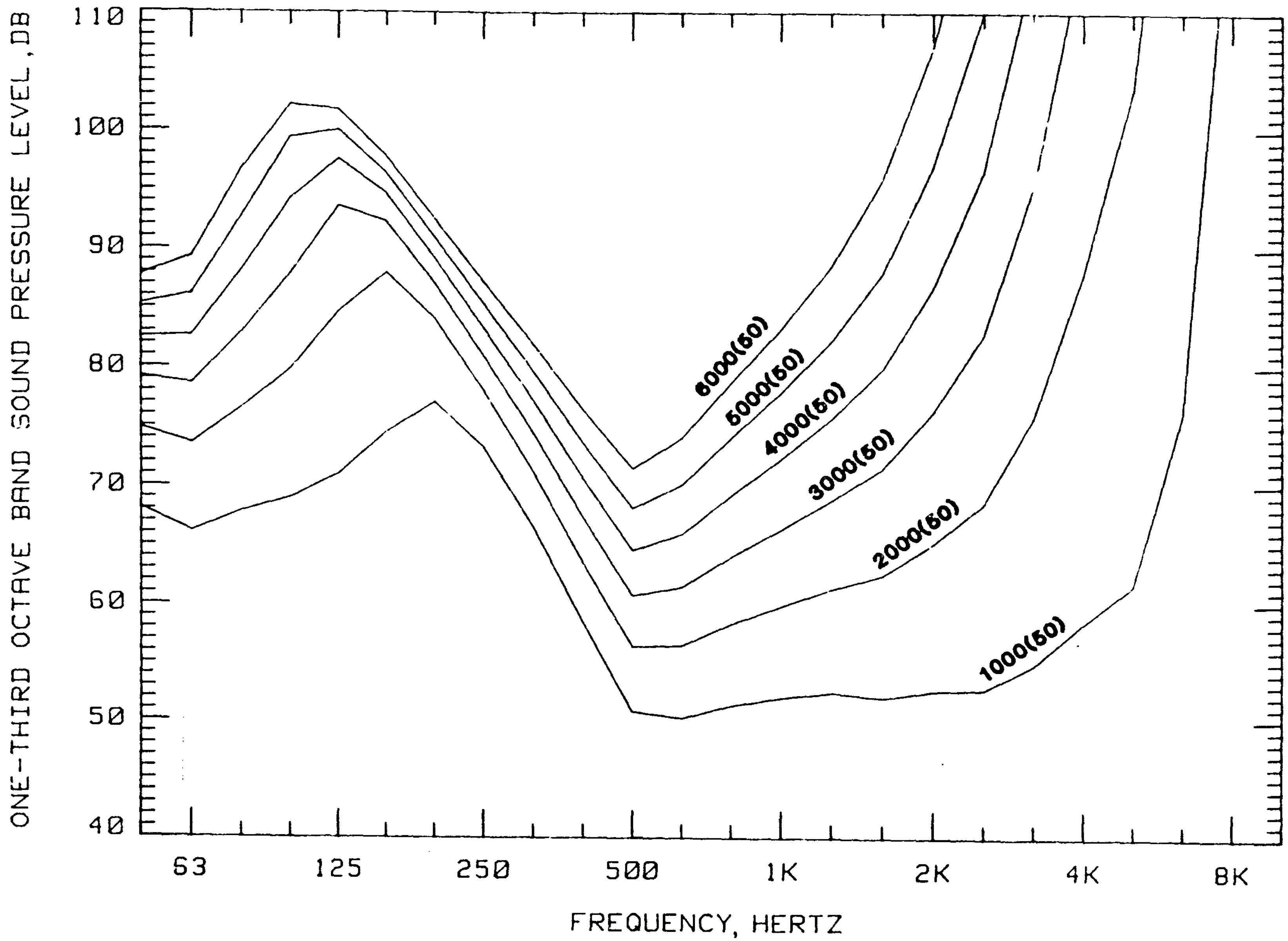
Note: The number in parentheses is the measurement distance in meters.

Figure 4A. Typical nondetectability limits for 10-400 meters.



Note: The number in parentheses is the measurement distance in meters.

Figure 5A. Typical nondetectability limits for 500-4000 meters.



Note: The number in parentheses is the measurement distance in meters.

Figure 6A. Typical nondetectability limits for 1000-6000 meters.

APPENDIX B

SUMMARY OF FACTORS WHICH FACILITATE OR IMPEDE SOUND PROPAGATION

SUMMARY OF FACTORS WHICH FACILITATE OR IMPEDE SOUND PROPAGATION

The following two tables have been prepared as an aid for understanding those conditions which, in actual field situations, will either facilitate (Table 1B) or impede (Table 2B) the propagation of sound of materiel. For example, materiel that just meets a specified nondetectability limit will almost certainly be inaudible during the day; however, it may be audible at night.

We estimate that the following factors which facilitate propagation may increase the sound level of the materiel at the receiver by approximately 15 dB. On the other hand, those factors which impede propagation may decrease the sound level of the materiel at the receiver by approximately 25 dB.

TABLE 1B

FACTORS FACILITATING SOUND PROPAGATION

*Nighttime conditions
  - temperature inversion
  - lower background noise due to diurnal variation
  - lower wind noise

*Downwind listener (wind below 9 km/hr)
*Acoustically hard surface (e.g., asphalt, water, etc.)
*Hot-moist and cold-dry weather
*Low background noise
*Source or receiver high above the ground

TABLE 2B

FACTORS IMPEDING SOUND PROPAGATION

*Daytime conditions
  - temperature lapse
  - higher background noise due to diurnal variation
  - greater wind noise

*Upwind listener
*Soft surface (e.g., snow, sand, etc.)
*Dense foliage
*Barrier
*Hot-dry weather
*High background noise
*Source or receiver close to the ground

APPENDIX C

COMPUTATION OF EXCESS ATTENUATION DUE TO GROUND EFFECT

COMPUTATION OF EXCESS ATTENUATION DUE TO GROUND EFFECT

The problem of spherical wave propagation near a ground surface of finite impedance was solved early in this century for radio waves and was later adapted to the acoustical case by Ingard (1951).

In **Figure 1C**, a point source of spherical harmonic waves is located at S at a height h_s above the ground. An image source I is located an equal distance underground directly below the source. At point R a receiver is situated at height h_r above ground and at a distance r_d from the real source and a distance r_r from the image source. The image appears to have a strength Q and to radiate waves which interfere with the direct wave D which travels from the real source directly to the receiver. The general expression which describes the sound pressure at the listener is then:

$$p = (A_d/r_d)\ \exp\{i(k_d r_d - \omega t)\} + Q\ (A_r/r_r)\ \exp\{i(k_r r_r - \omega t)\} \qquad (1)$$

where:

$$r_d = \sqrt{(h_s - h_r)^2 + R^2}\ , \quad r_r = \sqrt{(h_s + h_r)^2 + R^2}$$

$$Q = R_p + (1 - R_p)\ F$$

$$R_p = \frac{\sin\phi - Z_1/Z_2}{\sin\phi + Z_1/Z_2}$$, the plane wave reflection coefficient

$F(w)$ = the boundary loss factor

w = the numerical distance

$Z_1 = \rho c$, the characteristic acoustic impedance of the air

$Z_2 = R + i\ X$, the normal specific impedance of the ground

$k = 2\pi f/c$, the propagation constant for air

$\rho = 1.226\ kg/m^3$, the density of air at 15° C and 1.013×10^5 newtons/m^2 atmospheric pressure

c = 340.3 m/sec, the speed of sound under the above conditions

$\omega = 2\pi f$ where f is the frequency in Hertz

ϕ = the angle of incidence

A_d = the fluctuating direct wave amplitude

A_r = the fluctuating reflected wave amplitude

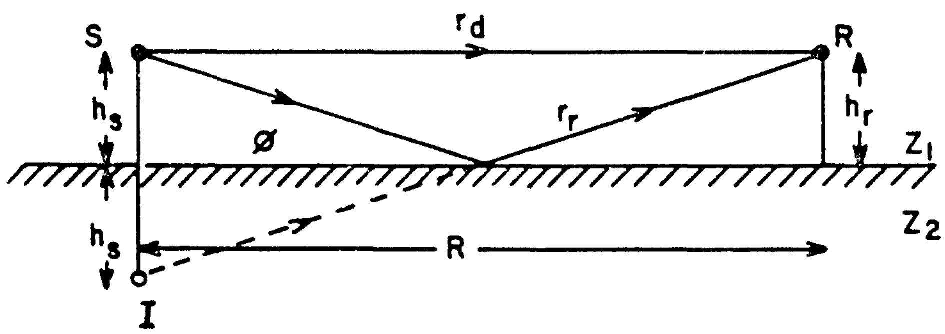


Figure 1C. Diagram showing location of source and receiver above flat ground of surface impedance Z_2.

The function F (w) is the boundary loss factor which describes the distortion of the spherical wave front by the ground. It is given by:

$$F(w) = 1 + 2iw^{1/2} \exp(-w) \int_{-iw^{1/2}}^{\infty} \exp(-\mu^2) d\mu \tag{2}$$

where:

$$w = {}^{1/2}\ ikr_r \ \frac{(\sin\phi + Z_1/Z_2)^2}{(1+\sin\phi \cdot Z_1/Z_2)} = \text{The numerical distance}$$

F is computed by the following convergent series:

$$F(w) = 1 + i\exp(-w)(\pi w)^{1/2} - 2\exp(-w) \sum_{n=1}^{\infty} \frac{w^n}{(n-1)!\,(2n-1)} \tag{3}$$

where the first seven terms of the infinite series give a sufficient error limit of 5 percent for values of $|w| < 5$. For values of $|w|$ beyond this it is more convenient to use the asymptotic series:

$$F(w) = -\sum_{n=1}^{\infty} \frac{(2n)!}{2^n n!\,(2w)^n} \tag{4}$$

where the first three terms give sufficient accuracy.

To proceed with the calculation, it is now necessary to introduce an acoustical model of the ground which describes the behavior of Z_2 as a function of frequency. One such model developed empirically by Delaney and Bazley (1970) for fibrous absorbent building materials has been successfully applied to a range of ground surfaces.

The real and imaginary parts of Z_2 are:

$$R/\rho c = 1 + 9.08(f/\sigma)^{-0.75} \tag{5}$$

$$X/\rho c = 11.9(f/\sigma)^{-0.73}$$

where σ is the flow resistivity in Rayls (cgs units). The values differ from directly measured values of the flow resistivity which need to be divided by 2 to account for the reduced porosity of soils and sands compared to fibrous absorbents (Attenborough, 1983; Chessell, 1977; Bolen & Bass, 1982).

Beyond an extensive description of the ground effect, the data of Parkin and Scholes (1965) show how closely it is linked with the effects of atmospheric turbulence and refraction. Turbulence in the form of varying sizes of eddy currents is always present at the ground surface due to instability of thermal and viscous boundary layers. The intensity ranges from low at night to high on a windy summer afternoon. The interference phenomena are particularly sensitive to these perturbations which have the effect of reducing the excess ground attentuation from the values calculated for a quiet atmosphere. Turbulence does not directly attenuate the sound, but rather scatters it so that sound energy deflects from higher altitudes into shadow zones near the ground and behind barriers. Listeners hear the sound vary over a range of intensities where the quiet levels are predicted by the preceding ground effect theory.

Turbulence causes random fluctuations in the magnitude and phase of both the direct and reflected waves. The net effect depends on the strength of the turbulence and on how the fluctuations along each path are correlated. For near grazing incidence, the two paths are close together so that this correlation would be expected to be high. In equation 1 these effects are introduced as fluctuating amplitudes and wave numbers of the direct and reflected waves respectively,

$$\begin{aligned} A_d &= 1+a_d \\ k_d r_d &= kr_d+d_d \\ A_r &= 1+a_r \\ k_r r_r &= kr_r+d_r \end{aligned} \qquad (6)$$

where k is the wave number with no turbulence. All quantities are assumed to be Gaussian, randomly distributed about a mean value of zero when a time average is taken over a statistically large number of fluctuations. The variances of a_d and a_r are furthermore assumed equal to $\langle a^2\rangle$, while the variances for d_d and d_r are both equal to σ_d^2. The close proximity of two paths in the same turbulent regions is accounted for by the amplitude covariance ρ_a and the phase covariance ρ_d.

The time averaged excess attenuation due to ground reflections in the presence of turbulence, when averaged over 1/3-octave bands, can now be derived over the distnce, R, from equation 1 as follows:

$$A_e(R) = 10\log_{10}\Big[(1+\langle a^2\rangle)(1+|Q|^2/r'^2) + \qquad (7)$$
$$(2|Q|/r')(1+\langle a^2\rangle\rho_a)\cos(\eta k(r_r-r_d)+\theta)\exp(-\sigma_d^2(1-\rho_d))\sin(\mu k(r_r-r_d))/(\mu k(r_r-r_d))\Big]$$

where:

$r' = r_r/r_d$

θ = phase angle of the image source relative to the real source

$\mu = (B - 1/B)/2$

$\eta = (B + 1/B)/2$

$B = 2^{1/6}$

To find the dependence of the statistical quantities $\langle a^2 \rangle$, $\sigma_d^{\,2}$, ρ_a and ρ_d upon measured values for distance, frequency, the strength and scale of wind, and temperature fluctuations, the theory of Karavainikov will be used (Daigle, 1980). The development assumes spherical wave propagation in a homogeneous and isotropic turbulent medium in the absence of a boundary. The acoustical index of refraction is written as $n=1+\mu$ where μ is the fluctuating component with variance $\langle \mu^2 \rangle$ on the order of 10^{-6}, and L is a measure of the scale of the turbulence. The amplitude and phase fluctuations can be found from:

$$\langle a^2 \rangle = x / (1 + (11/4)x) \quad , \quad \text{for } x <= 1 \tag{8}$$

$$= 0.27\, x^{.33} \quad , \quad \text{for } x > 1$$

where:

$$x = (I1 - I2) / 2$$

$$\sigma_d^{\,2} = (I1 + I2) / 2$$

$$I1 = \pi^{1/2} \langle \mu^2 \rangle k^2 r_d L$$

$$I2 = \pi^{1/2} \langle \mu^2 \rangle k^2 r_d L \, \frac{1}{\Delta^2 (\Omega+1) (8\Omega)^{1/2}} \left\{ \frac{\Delta\Omega}{2} \ln \frac{1+\Delta(2\Omega)^{1/2}}{1-\Delta(2\Omega)^{1/2}} + \right.$$

$$\left. \tan^{-1} \frac{\Delta\Omega}{1-\Delta(2\Omega)^{1/2}} - \tan^{-1} \frac{\Delta\Omega}{1+\Delta(2\Omega)^{1/2}} \right\}$$

$$\Omega = (1 + 1/\Delta^2)^{1/2} - 1$$

$$\Delta = r_d / (kL^2)$$

For both propagation over hard (asphalt) and finite impedance (grass) boundaries and at large source-receiver separations the theory shows that ρ_a and ρ_d depend on the ratio of the maximum path separation to the turbulence scale parameter L. Parkin and Scholes (1965) produced data which compared favorably to the predicted values using $\langle \mu^2 \rangle = 0.6\times10^{-6}$; L=1.1 meters; $\rho_a = \rho_d = 0.8$ and $\sigma = 200$ cgs units. A sensitivity analysis shows strong dependence on $\langle \mu^2 \rangle$ and relatively minor dependence on the amplitude and phase covariances.

APPENDIX D

CONVERSION OF 1/3-OCTAVE SPECTRUM TO AUDITORY FILTER SPECTRUM

CONVERSION OF 1/3-OCTAVE SPECTRUM TO AUDITORY FILTER SPECTRUM

Fidell, Horonjeff, Teffeteller, & Green (1980) have found that people base their detection decisions on the internal auditory bands which are wider than one-third of an octave for frequencies below 1000 Hz. The amount of signal received in each of these auditory filters centered on 1/3-octave center frequencies can be calculated by a weighted sum of the 1/3-octave band signal information as follows:

$$L_A(i) = 10 \log_{10} \sum_{j=-2}^{2} 10^{L(i+j)/10} \, w(i,j)$$

where:

$L_A(i)$ = auditory filter band level, dB

$L(i)$ = signal level in the i-th 1/3 octave band, dB

$w(i,j)$ = the weight coefficients for each 1/3 octave band.

Values for the weight coefficients together with effective auditory filter bandwidths, W, for calculating the signal detection theory corrections are given in Table 1D.

TABLE 1D

WEIGHT COEFFICIENTS AND AUDITORY BANDWIDTHS FOR COMPUTING AUDITORY FILTER BAND LEVELS

i	f(Hz)	W(Hz)	w(i,-2)	w(i,-1)	w(i,o)	w(i,1)	w(i,2)
1	50	133.0	0	0	1	1	0.5
2	69	115.9	0	0.5333	1	0.6683	0.45
3	80	105.7	0.3048	0.4355	1	0.5176	0.3846
4	100	100.8	0.1521	0.3565	1	0.3999	0.1321
5	125	98.7	0.07568	0.2917	1	0.3090	0.04539
6	160	98.7	0.03776	0.2388	1	0.2388	0.01560
7	200	98.7	0	0.1950	1	0.1845	0
8	250	102.2	0	0.1596	1	0.1429	0
9	320	117.3	0	0.1306	1	0.1104	0
10	400	122.5	0	0.1069	1	0.08531	0
11	500	140.0	0	0.08750	1	0.06592	0
12	640	161.0	0	0	1	0	0
13	800	192.5	0	0	1	0	0
14	1000	231.0	0	0	1	0	0
15	1250	290.9	0	0	1	0	0
16	1600	366.1	0	0	1	0	0
17	2000	461.0	0	0	1	0	0
18	2500	580.3	0	0	1	0	0
19	3200	730.5	0	0	1	0	0
20	4000	919.8	0	0	1	0	0
21	5000	1157.9	0	0	1	0	0
22	6400	1457.5	0	0	1	0	0
23	8000	1835.2	0	0	1	0	0
24	10000	2310.1	0	0	1	0	0